MeerKAT Optics Design

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Contents

- Overview of modelling techniques
- Current stage in the KAT project
- MeerKAT specification
- Questions
- Way forward

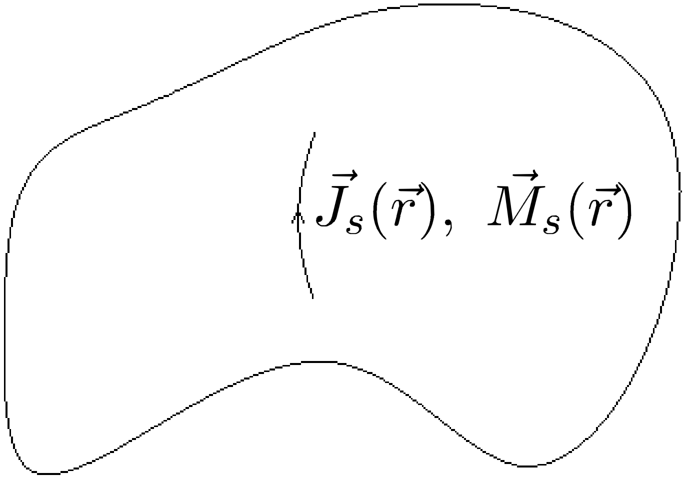
Modelling Techniques

- **C**omputational **E**lectro**m**agnetics
  - Reasonably mature, more trusted in industry
  - Significant increase in computing power
- Commercial codes
  - Testing, validation & maintenance
  - Documentation
- Different levels of approximation
  - Method of moments → MLFMM
  - Physical optics (with diffraction)
  - Geometrical optics → Aperture integration

$\vec{J}_s(\vec{r})$

Method of Moments

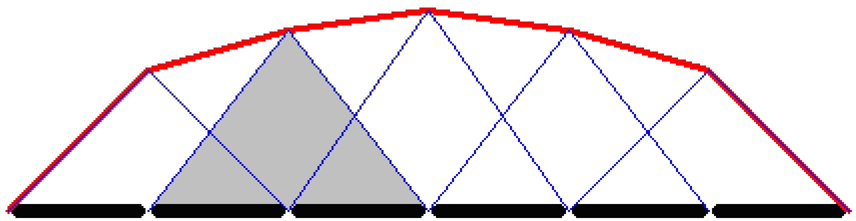
- Small complex structures, e.g. feed horn
- Current flowing on surfaces
  - Electric current on metal surfaces
  - Electric and magnetic on dielectric surfaces
- Current expanded as sum of basis functions
  - $\vec{J}_s = \sum_{n=1}^{N} \alpha_n \vec{f}_n$
- Entire domain possible
- Typically triangular
  - Very general



$\vec{J}_s(\vec{r})$

Method of Moments

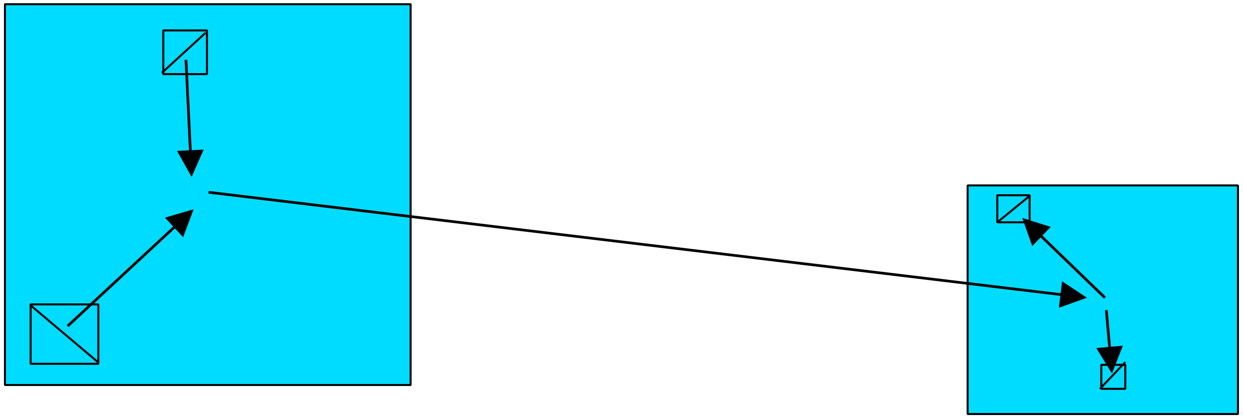
- Wire segments in 2D



- Simple field calculation
  - $$\vec{E}(\vec{r}) = \sum_{n=1}^{N} \alpha_n \int_{basis} \overline{\overline{G}}(\vec{r},\vec{r}\,') \,.\, \vec{f}_n(\vec{r}\,')\, dA'$$
- Sampled boundary condition (basis function)
- Dense matrix equation – “Full wave solution”
- Memory ∝ N^2 ∝ f^4; Solution time ∝ N^3 ∝ f^6
- Example: FEKO

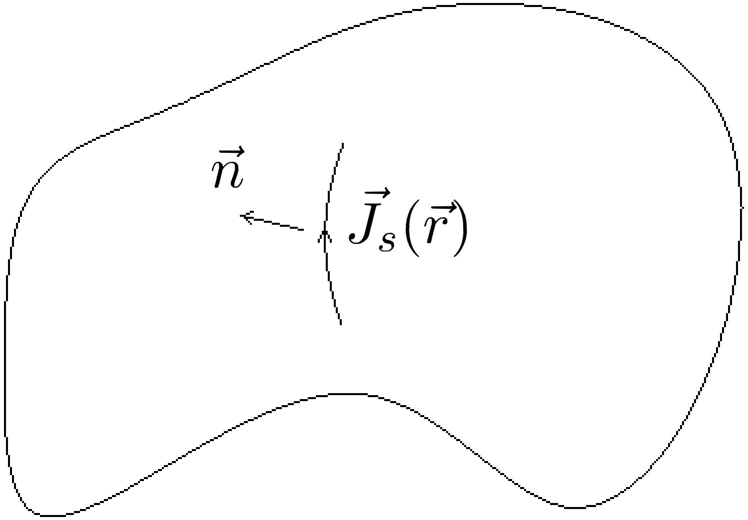
Multilevel Fast Multipole Method

- Larger problems, e.g. dishes at L-band
- Group basis function interaction in blocks
- Iterative solution of sparse matrix
- Memory / Solution time ∝ N log N ∝ f^2 log f
- Still a full wave solution, same accuracy



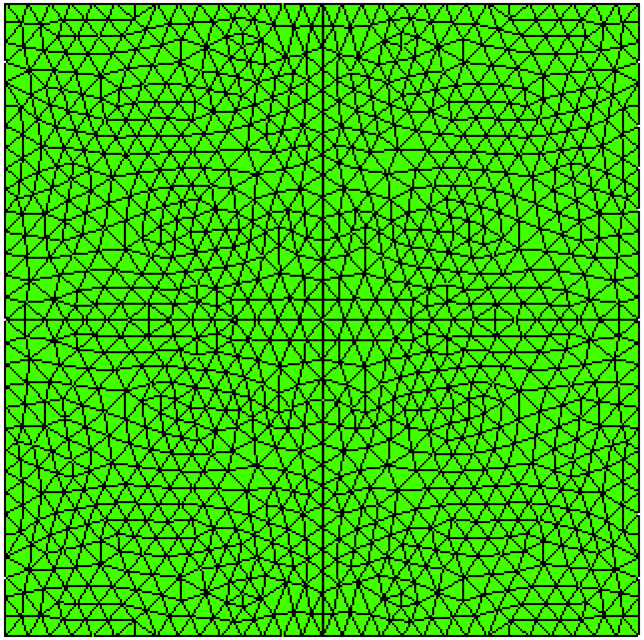
Physical Optics

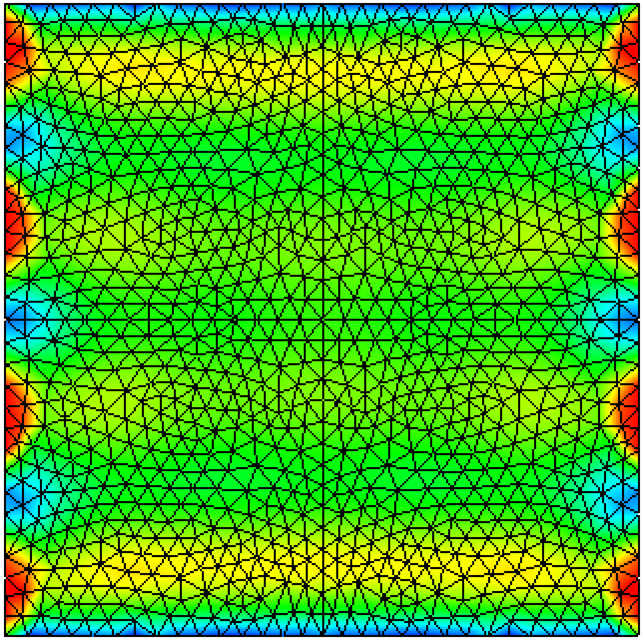
- Even larger problems, dishes at X-band
- Current approximated from incident field
  - $\vec{J}_s(\vec{r}) = 2\vec{n} \times \vec{H}_i(\vec{r})$
- Field calculated from current integral
- Can hybrid this with MoM
  - Modify MoM currents
  - One directional coupling
  - Not for large MoM regions



Physical Optics, PTD extension

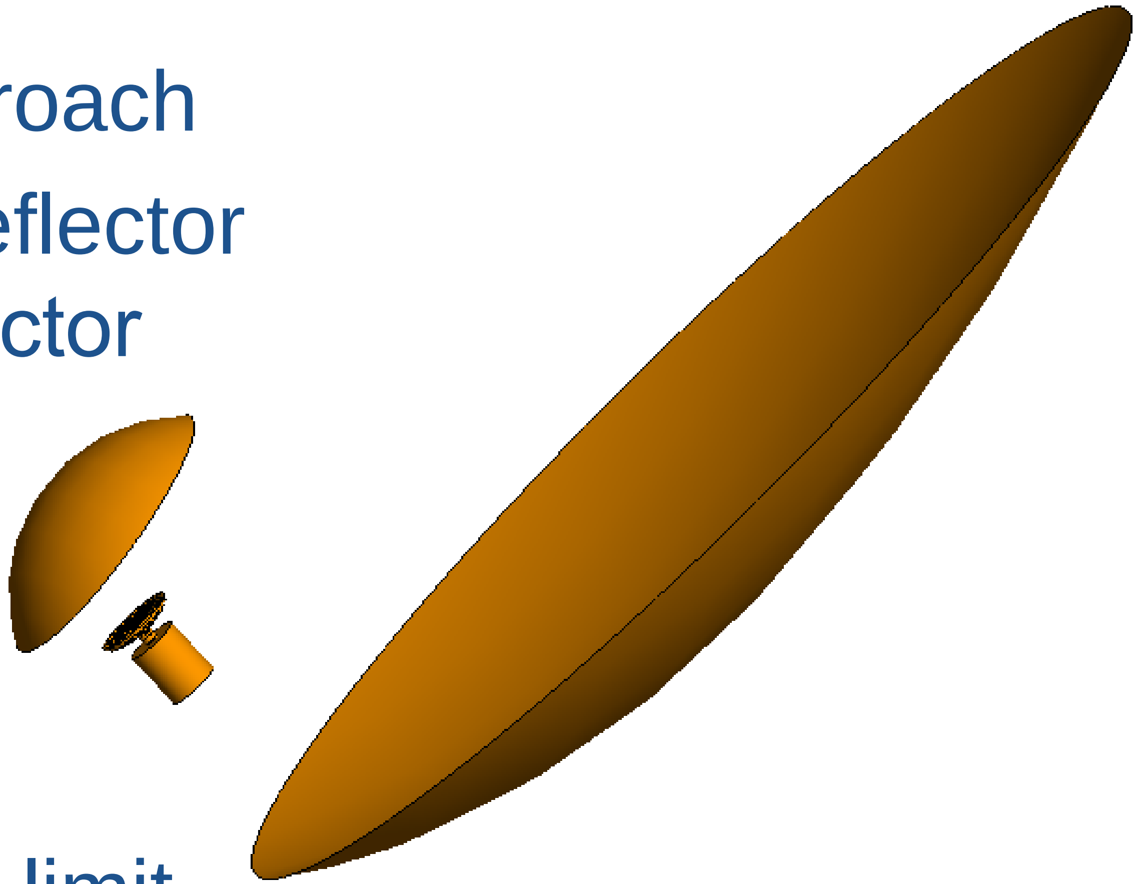
- PO current independent of edge effects
- Physical theory of diffraction (PTD) correction





Physical Optics

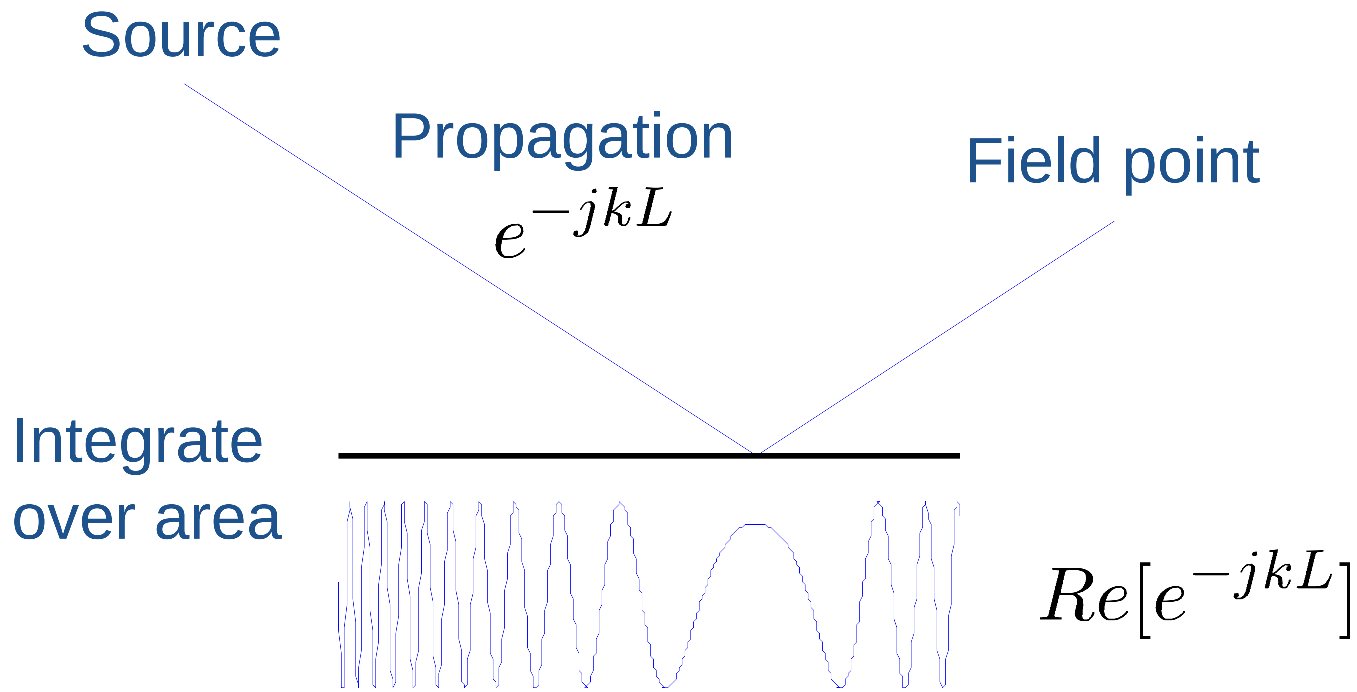
- Step-wise approach
- Feed → sub-reflector
  → main reflector
  → Far field



- Low frequency limit
- Example: GRASP9; FEKO (single reflection)

Geometrical Optics

- Even higher in frequency
- Specular reflection / stationary phase



Geometrical Optics

- Rays of expanding cones
- Reflected tangential to surface normal
- Ray “density” modified for curved surfaces
- For dishes
  - Refined by doing only up to aperture
  - Example: cassbeam (Walter Brisken)
- Fails if radius of curvature too small
- Add diffraction terms – UTD
  - Same stationary phase concept with edges

Modelling software

- FEKO
  - Full wave analysis with MLFMM
  - Parallelised for large machines
    (leo cluster with 176 cores, groups of 12 – 32)
  - Rather expensive if not inside EMSS
- GRASP9
  - Full version & multiple GRASP SE installation
  - 20 000 Euro
- Pick according to frequency range

Contents

Current stage in the KAT project

KAT Phases

- XDM (Done)
  - Single antenna HARTRAO
  - Original KAT = 21 x XDM

- KAT-7 (7 antennas in Karoo)
  - Meant as engineering model
  - Being commissioned

- MeerKAT (64 antennas in Karoo)
  - PDR (July 2011)
  - *Currently finalising dish specification*

Contents

MeerKAT specification

What is fixed

MeerKAT Specifications

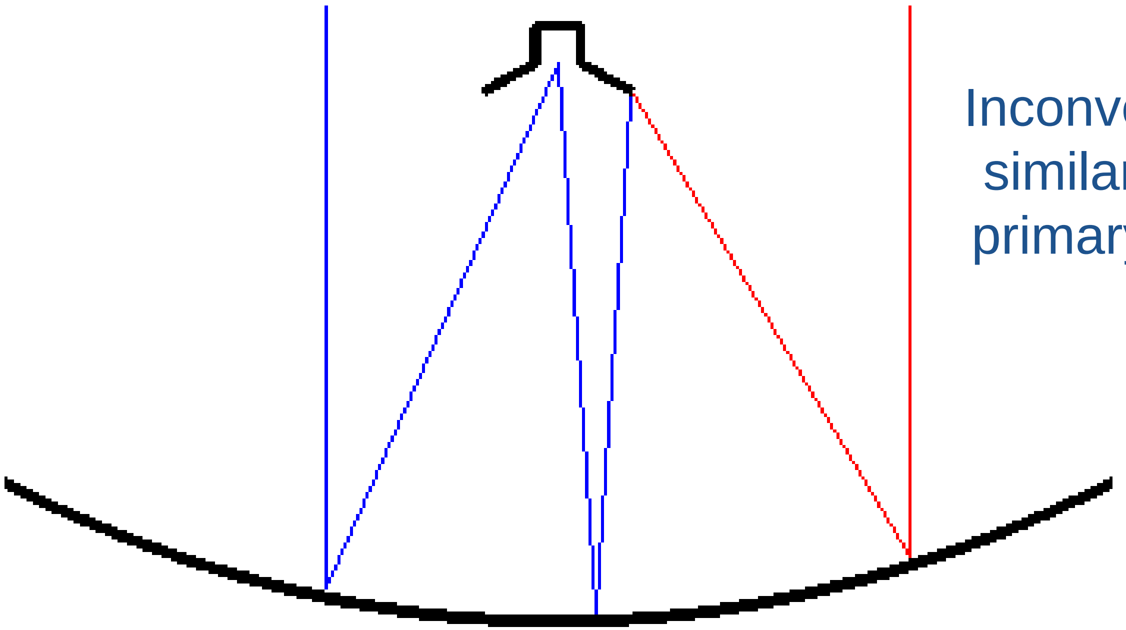
- Offset Gregorian
- Effective focal length / Feed illumination angle
  - Fixed at $F_{eq}/D = 0.55$
- Final optics selection
  - Finalising layout
  - Mechanical trade-off pending
- Feed low

Offset Gregorian Selection

- ***Small dish*** array
  - – Really compound “per antenna” negative effects
  - – Cannot “copy” conventional wisdom
- Offset Gregorian v. Cassegrain
  - – Cassegrain have narrow feed angles
  - – Decision driven by size of the feed horns
- Offset Gregorian v. Prime focus
  - – Multiple feeds
    - There is “storage” real estate outside the optical path

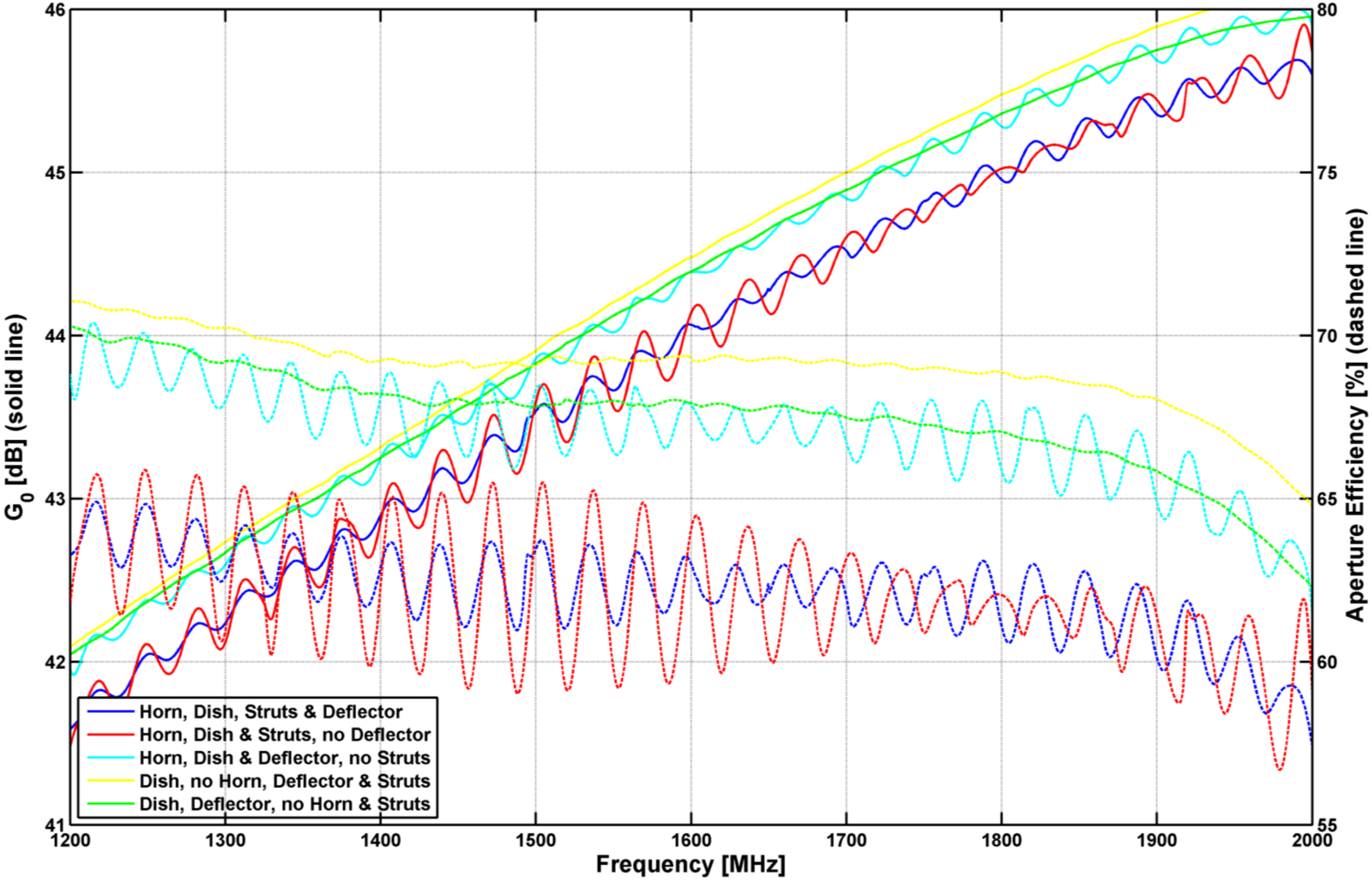
Offset Gregorian v. Prime Focus

- Prime focus feed blockage
  - Result in gain ripple (re-radiation from feed)
  - Effect would be smaller on a large dish

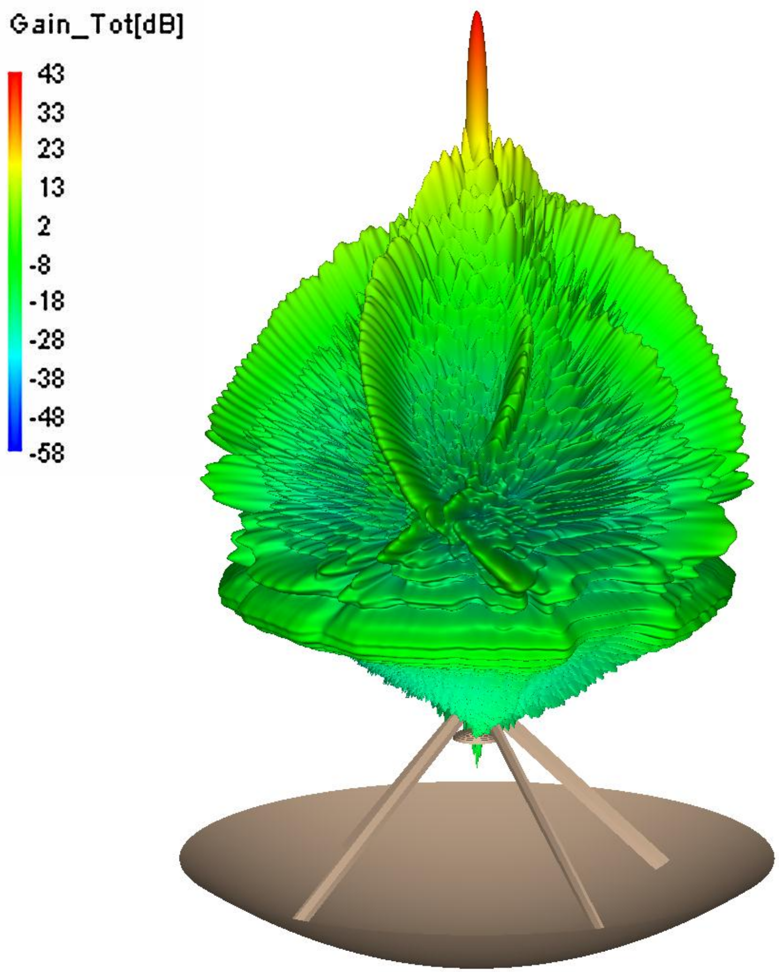


Inconveniently similar to the primary beam

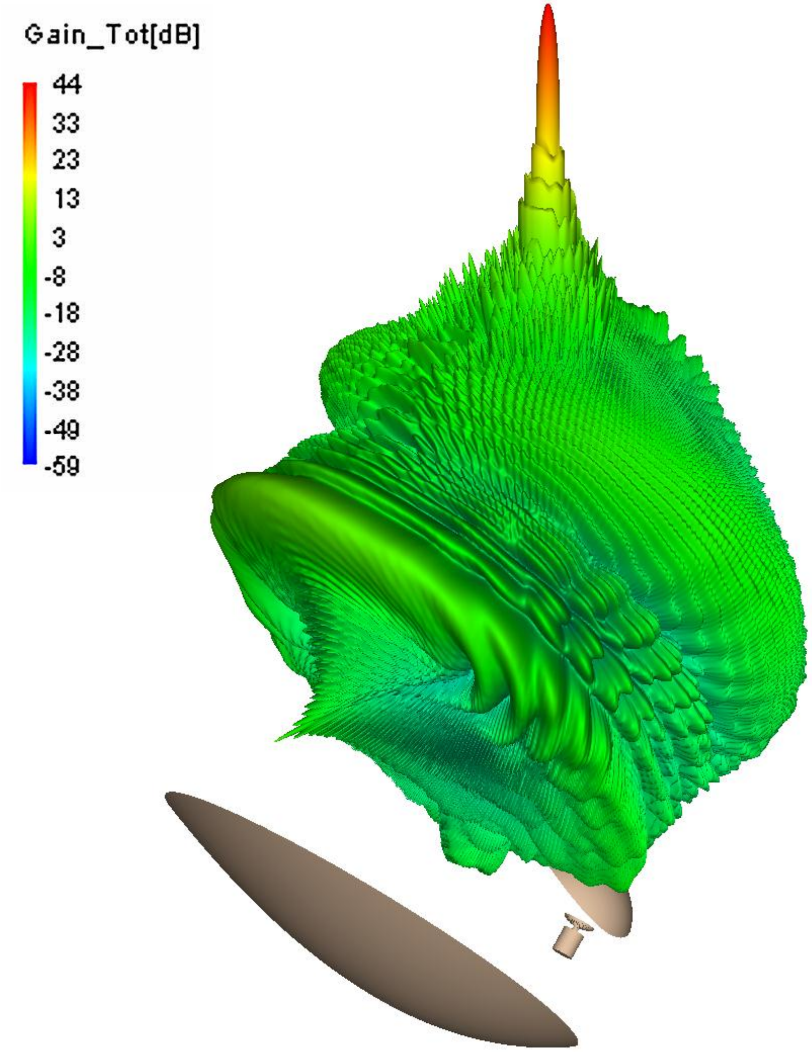
Prime Focus (KAT-7) gain ripple



Offset Gregorian v. Prime Focus



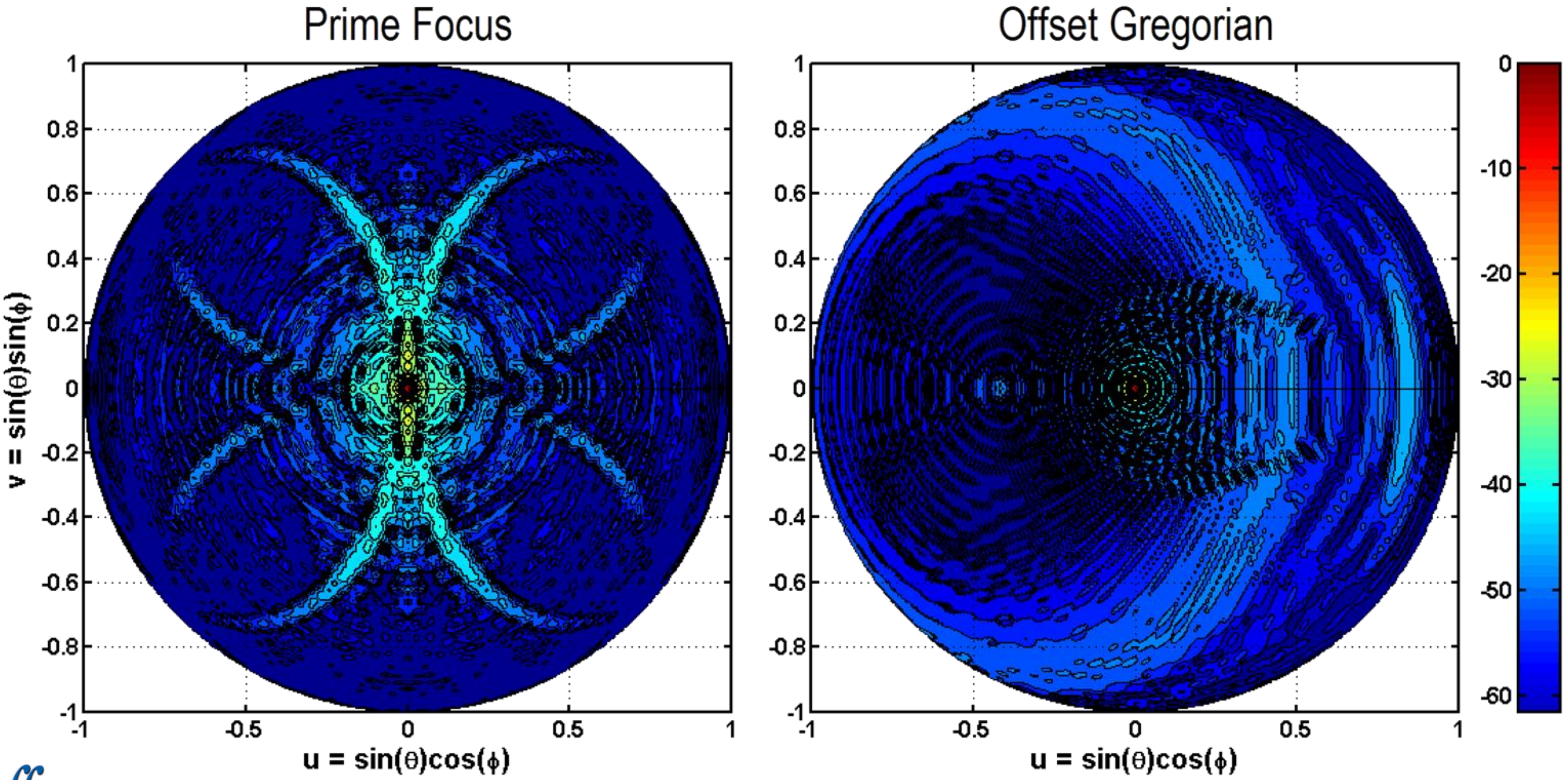
Prime focus



Offset Gregorian (Vertical-pol)

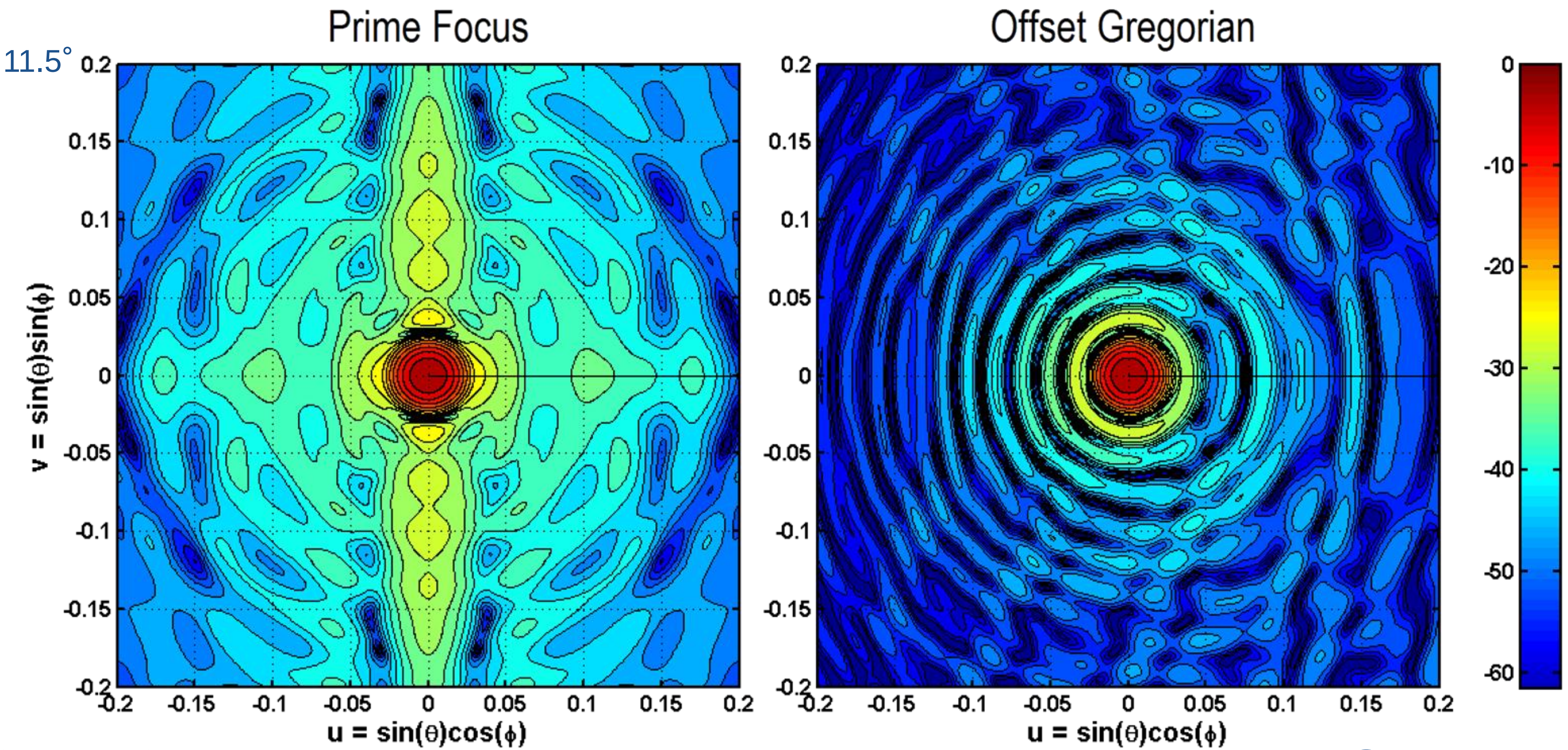
Offset Gregorian v. Prime Focus

- Far out side-lobes (tipping and $T_{spill\text{-}over}$)



Offset Gregorian v. Prime Focus

- Near side-lobes rotational variation



1.4 GHz

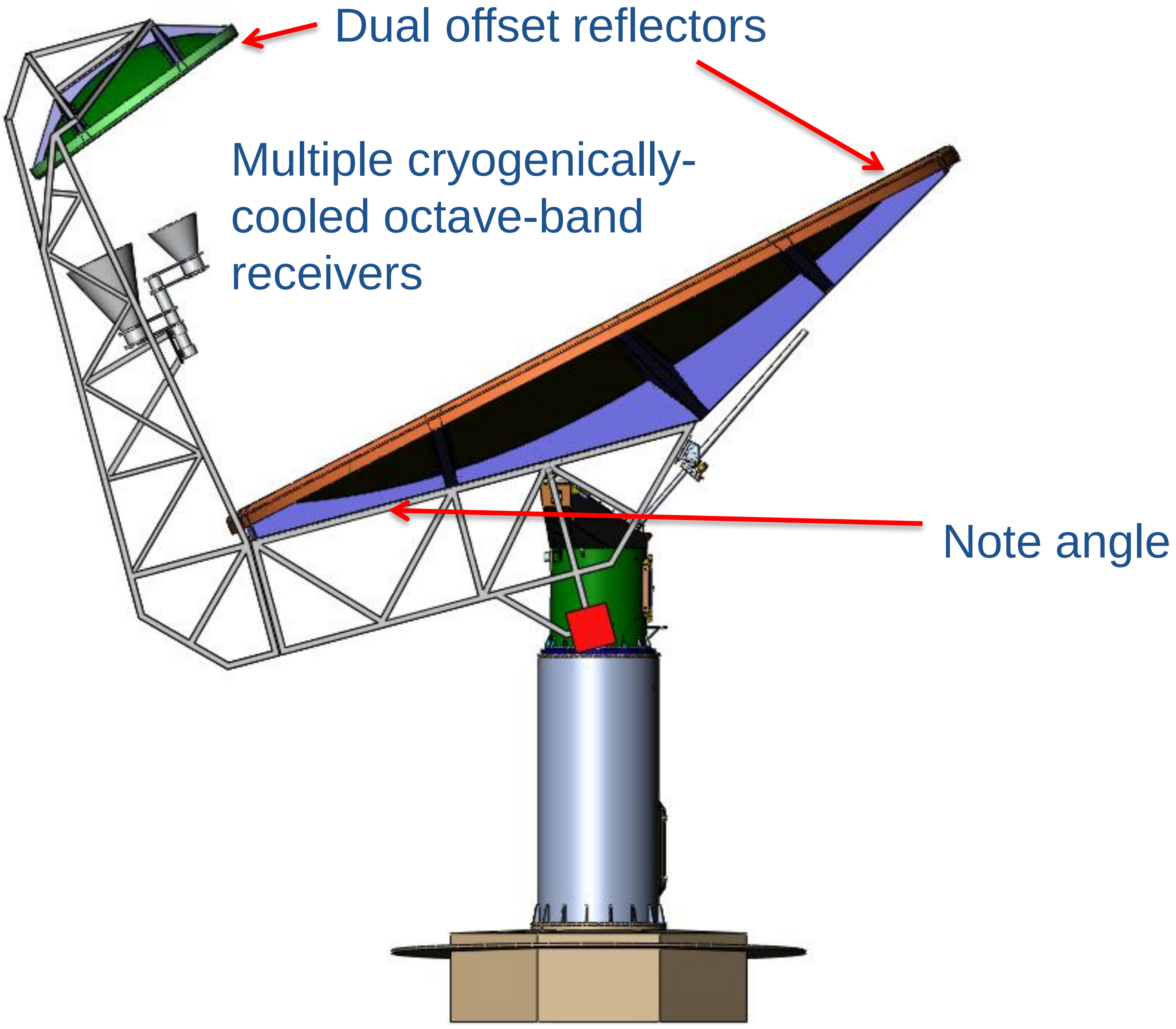
Offset Gregorian v. Prime Focus

- Allow stronger edge illumination
- No strut blockage
  - A_e about 10% higher for same projected area
  - Clean patterns
    - RFI reduction
    - T_{sys} improvement at lower elevations
    - Can get low side-lobes (also traded against T_{spill})
- Cross-polarisation need not be worse
  - Reflector orientation (Mitzugutch)
  - Flatter equivalent system

Offset Gregorian Selection

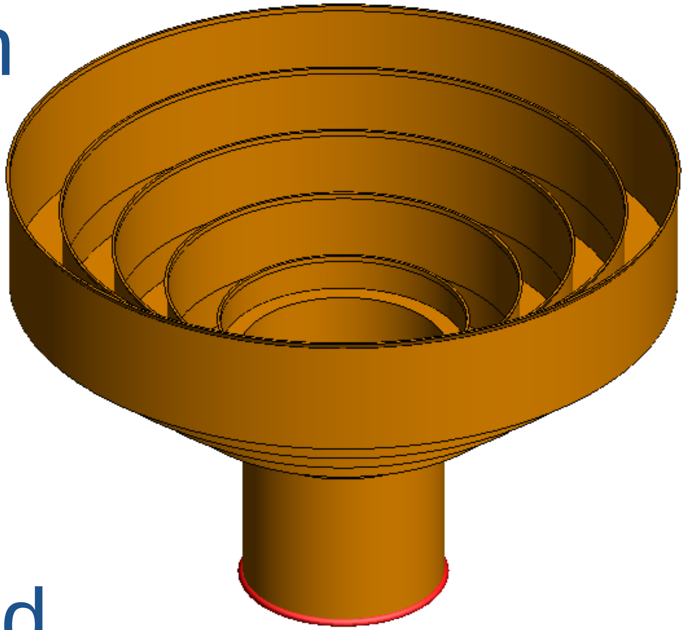
- Also not a perfect solution
  - Mechanical complexity
  - More surface and cost
  - Two surfaces contributing to phase (Ruze) error
    - Offset reduce main reflector impact by 10 - 15%
  - Lost sky coverage
    - Significant impact on simultaneous observation
  - Shadowing increase minimum spacing
  - Requirements of “Phased” array feeds?
- Offset Gregorian still the best option

Offset Gregorian Selection

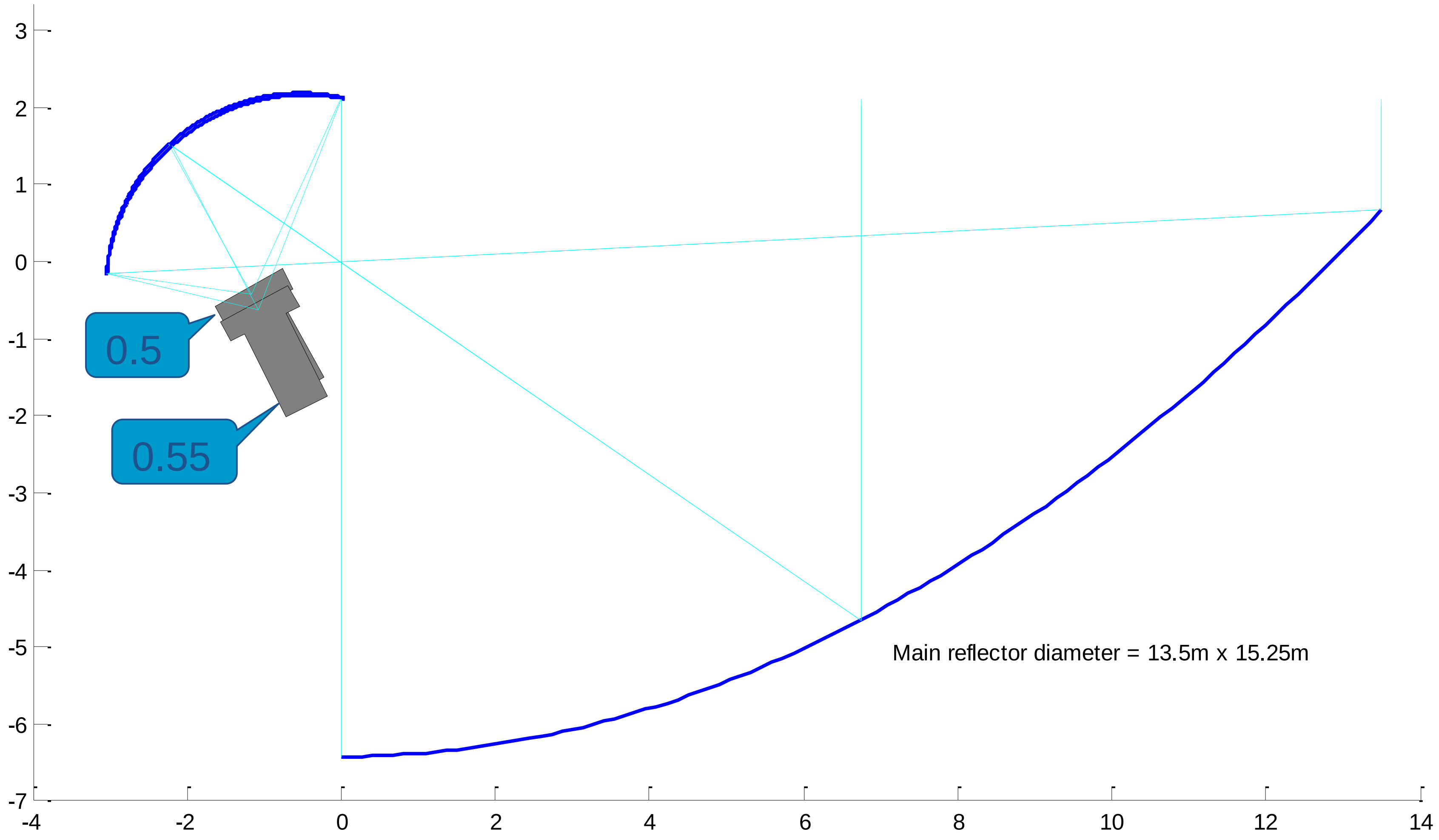


Feed Angle Selection

- Compact 1-1.75 GHz horn
- Optimised for dishes with different focal ratios
- “Flatter” systems capture less of the feed energy
- In deeper systems the feed get in the way of the optical path
- Flat optimum $F_{eq}/D = 0.5 – 0.6$



Feed Angle Selection

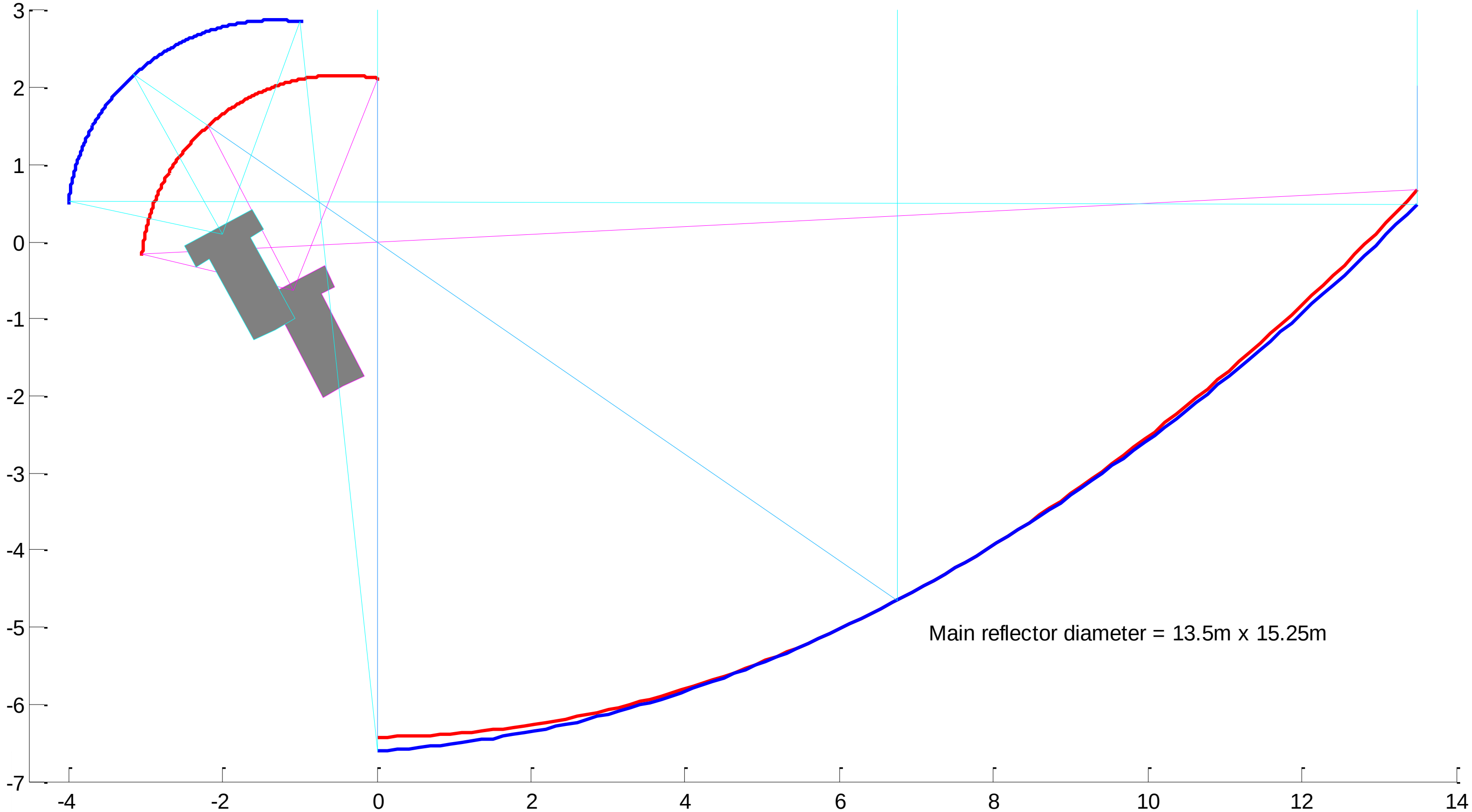


MeerKAT Optics Selection

- Blank page
  - Only feeds fixed (by us), dish optics still open
  - Daunting parameter space
    - Six degrees of freedom on dual reflector system
  - Mechanical trade-off dependent on design
    - MeerKAT / TDP boom / main reflector length
  - Want the best “as built” performance
- Main reflector sized for sensitivity
- Sub-reflector sized for road transport
- Cross-polarisation (Mitzugutch)

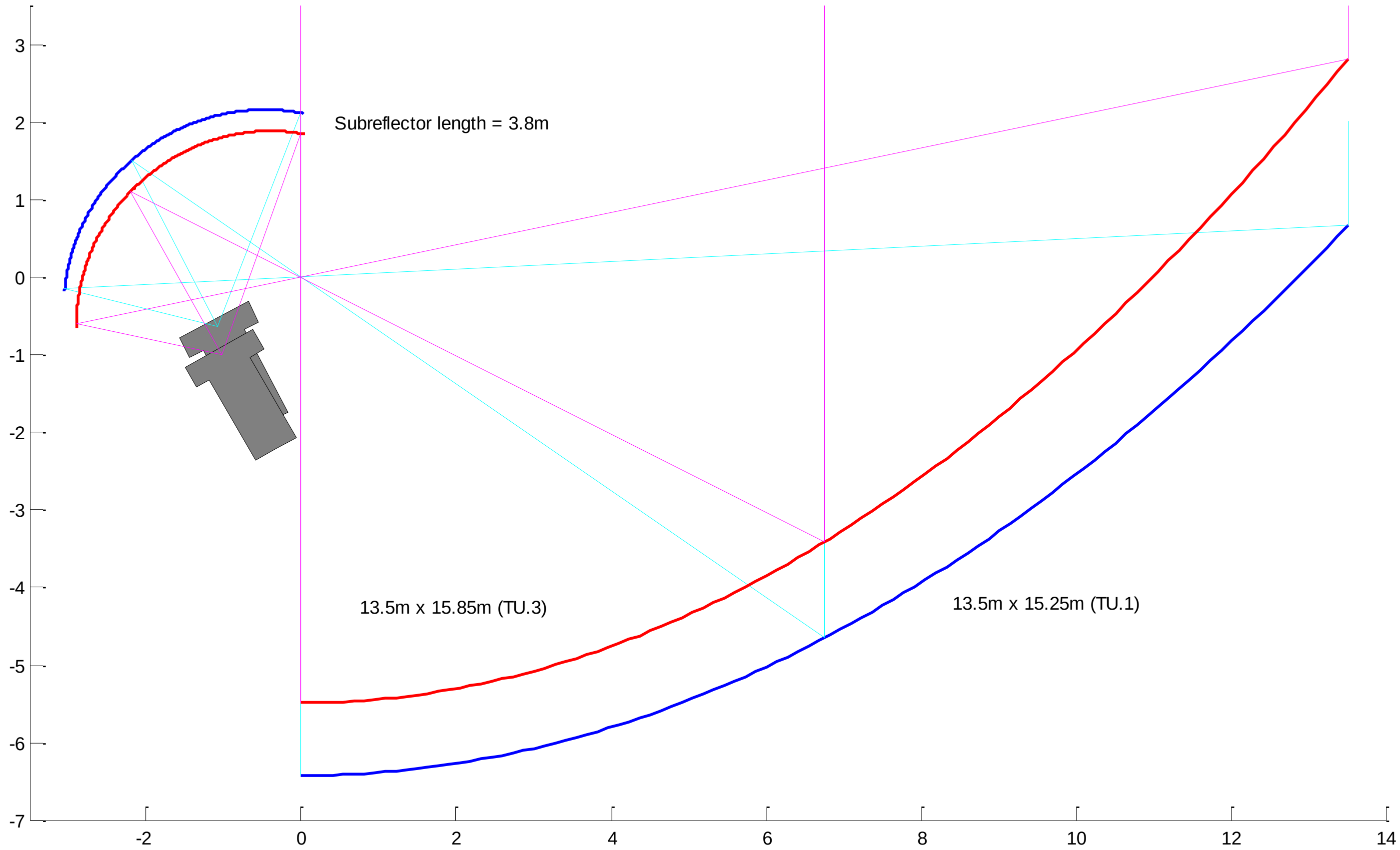
MeerKAT optics selection

- Sub-reflector clearance increases feed boom length – prefer no clearance



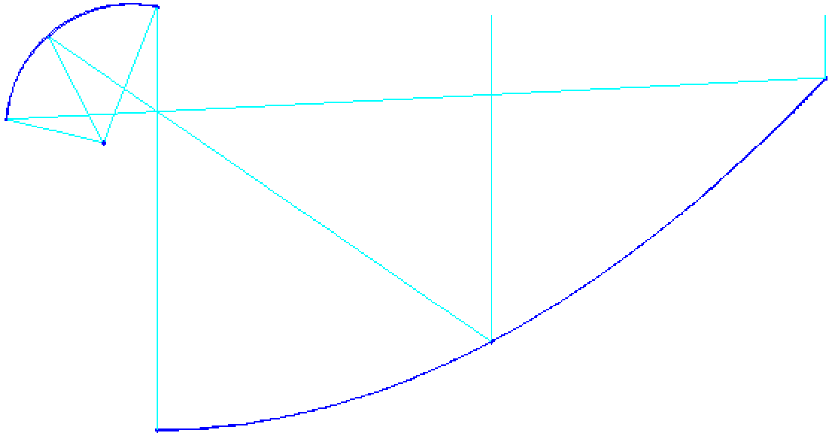
MeerKAT optics selection

- Last trade-off
  Main reflector size v. feed boom length

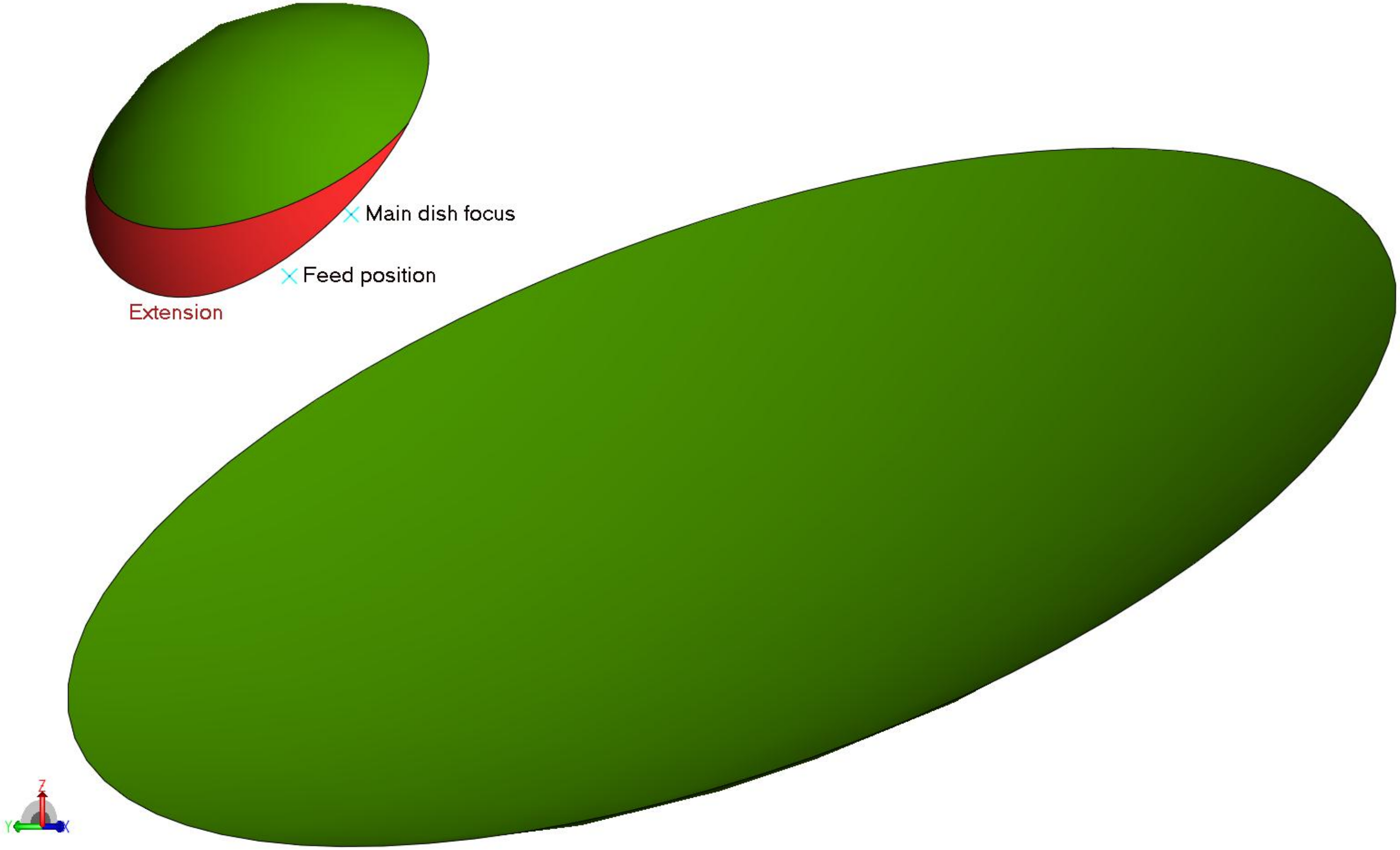


Feed high versus feed low

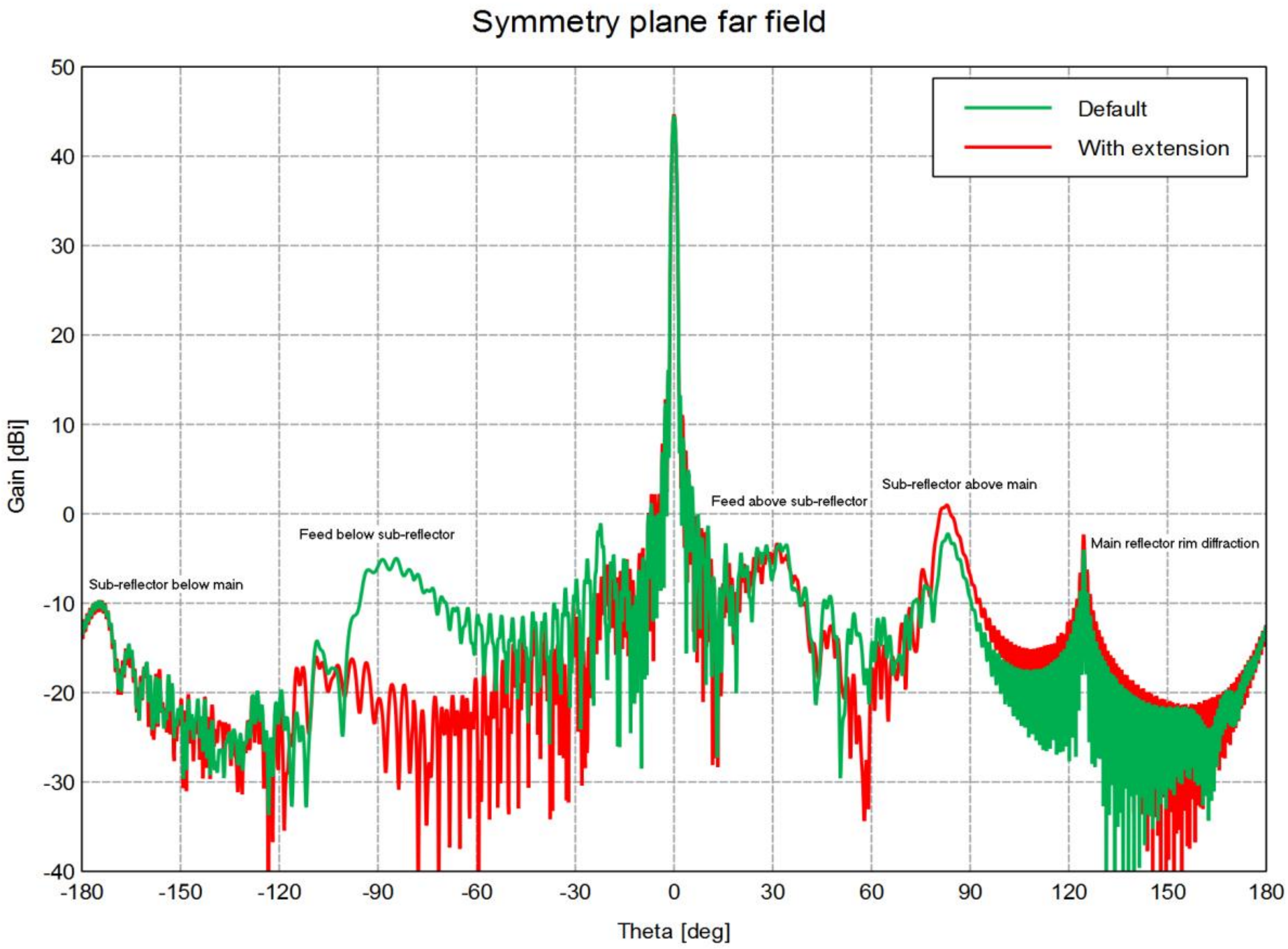
- Feed low
  - Allows easy access to the feeds
  - Spill-over better controlled
- "Sail" upright
  - Not "ideal" stowing



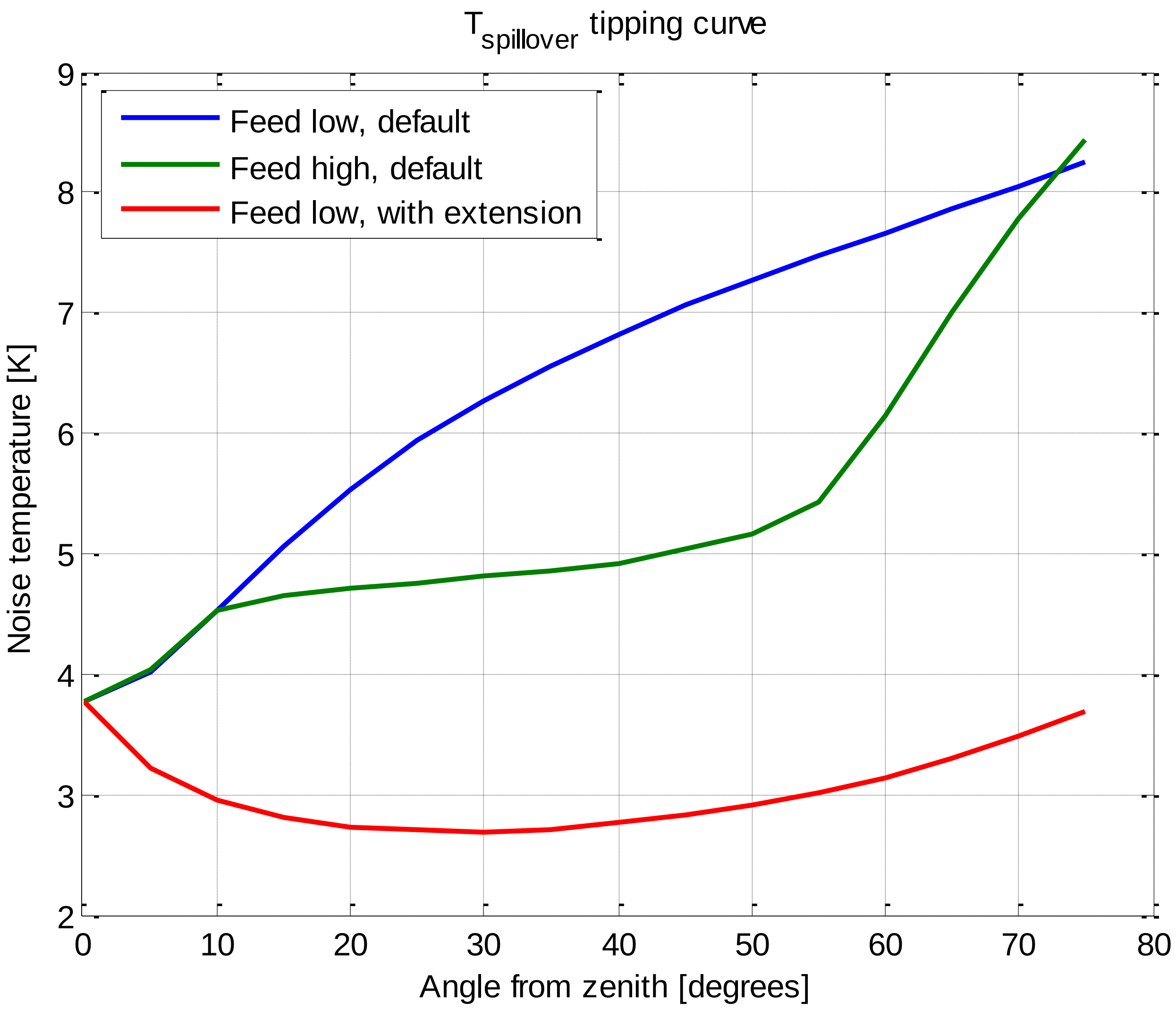
Feed high versus feed low



Feed high versus feed low



Feed high versus feed low



Contents

Questions

What is still undecided

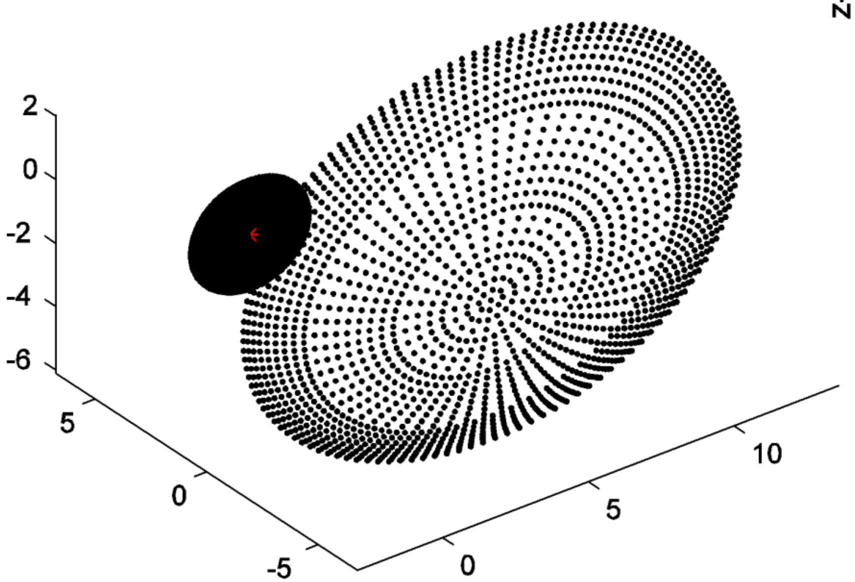
Issues

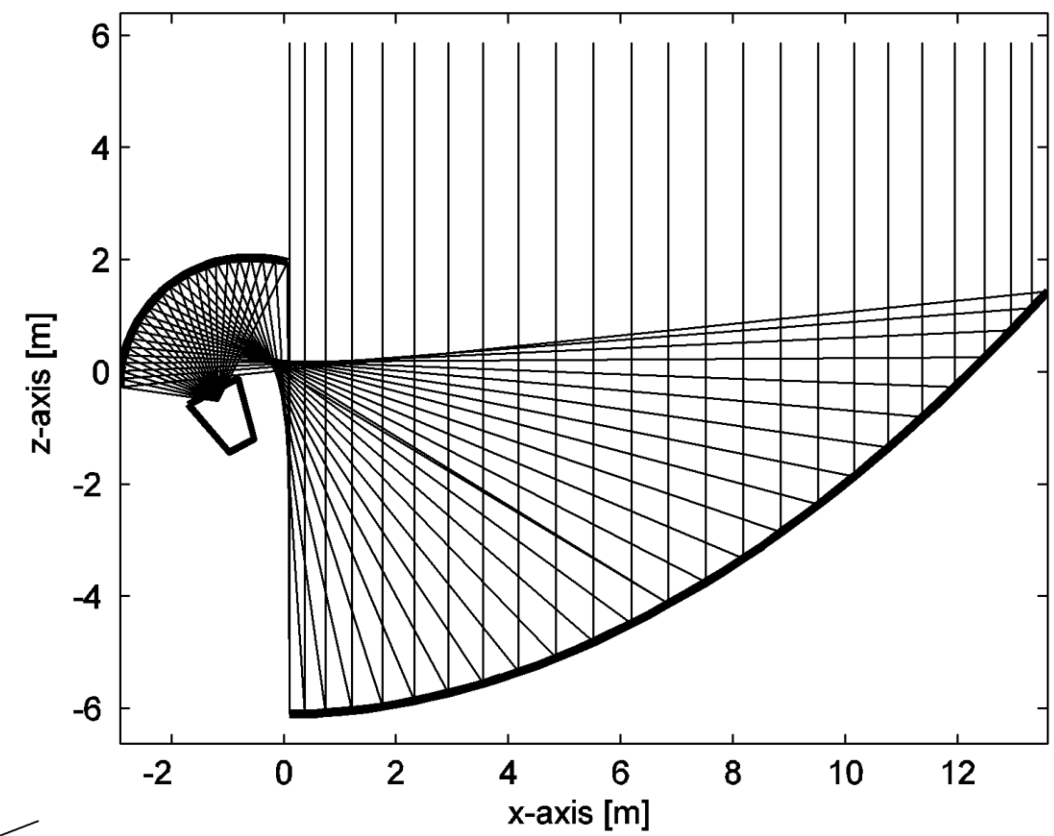
- Shaping
  - Trade-off between side-lobes and efficiency
- Designing the extension
- Beam offset ("Squint" defined otherwise)
- Tolerance
- Slots (between panels) impact

Shaping

- Increase the parameter space: shaping
  - Capture more feed energy
    - Deeper effective system for same feed
    - Need not increase side-lobes
    - Typically a small impact on radio astronomy systems
  - Distribute pattern to use surface better
    - Will increase side-lobes
  - Much easier to control aperture field
    - Sensitive to feed pattern
      - Deep taper sensitive to error in centre of sub-reflector
      - Hard illumination has spill-over loss and diffraction

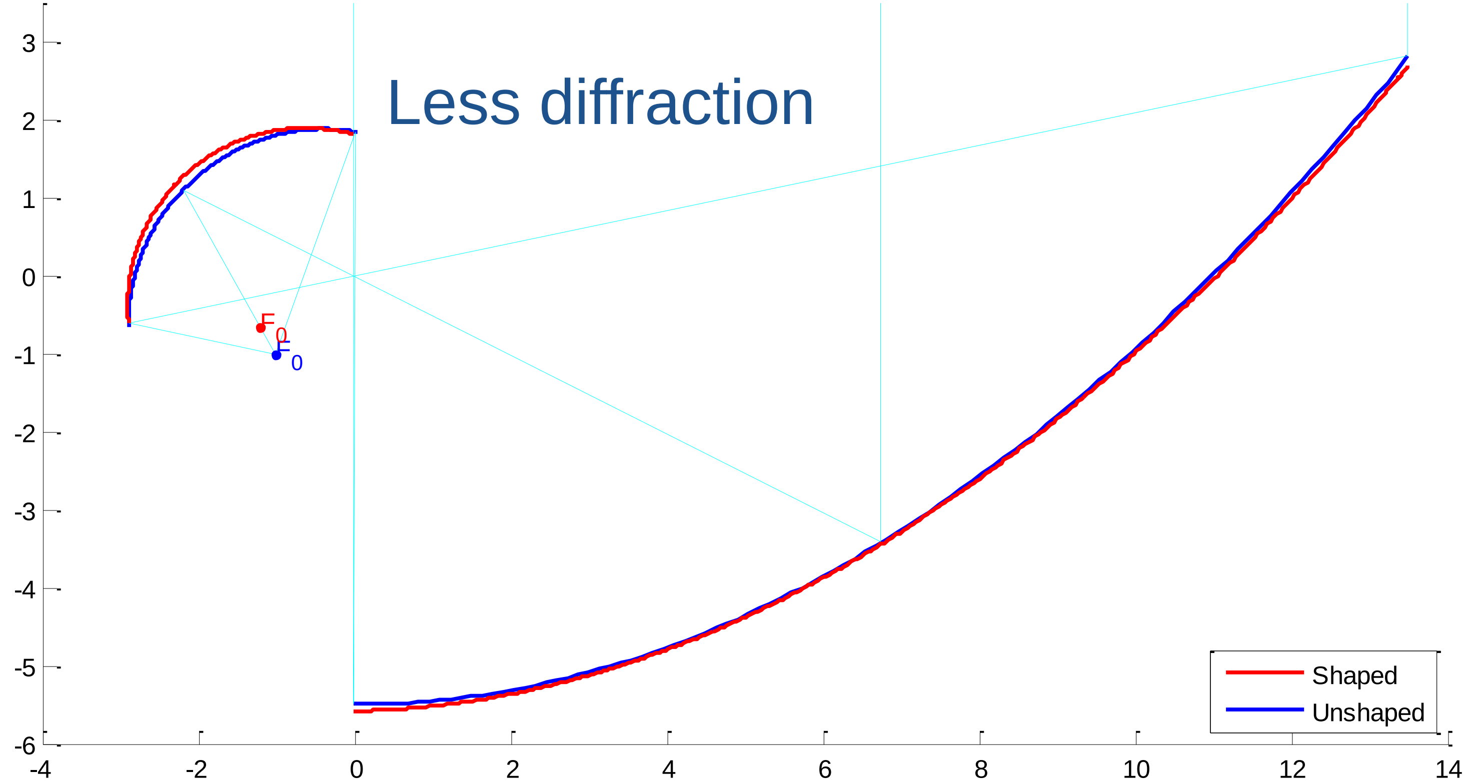
Shaping





Shaping

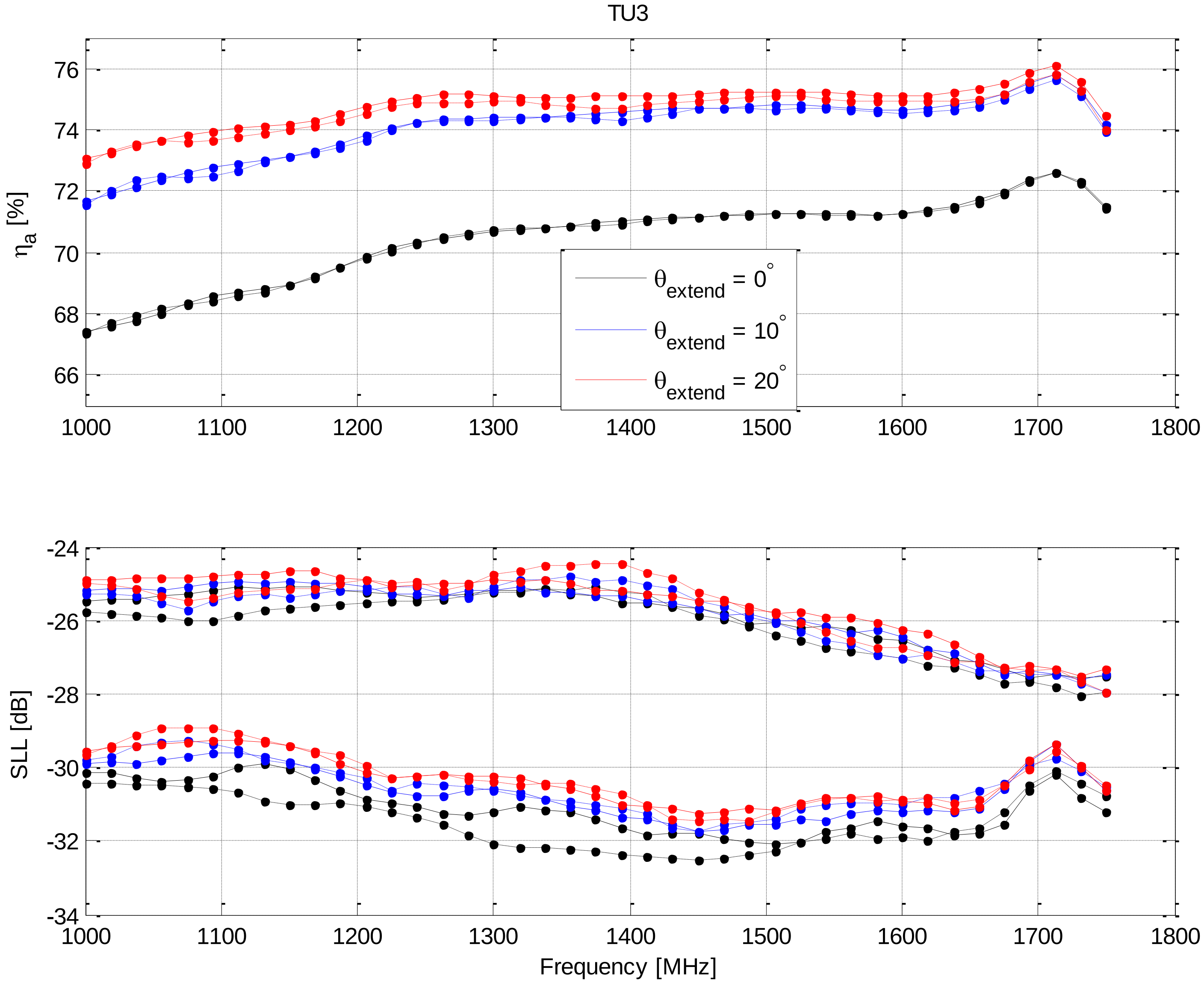
- Almost no mechanical reflector difference
  Feed position further from main dish



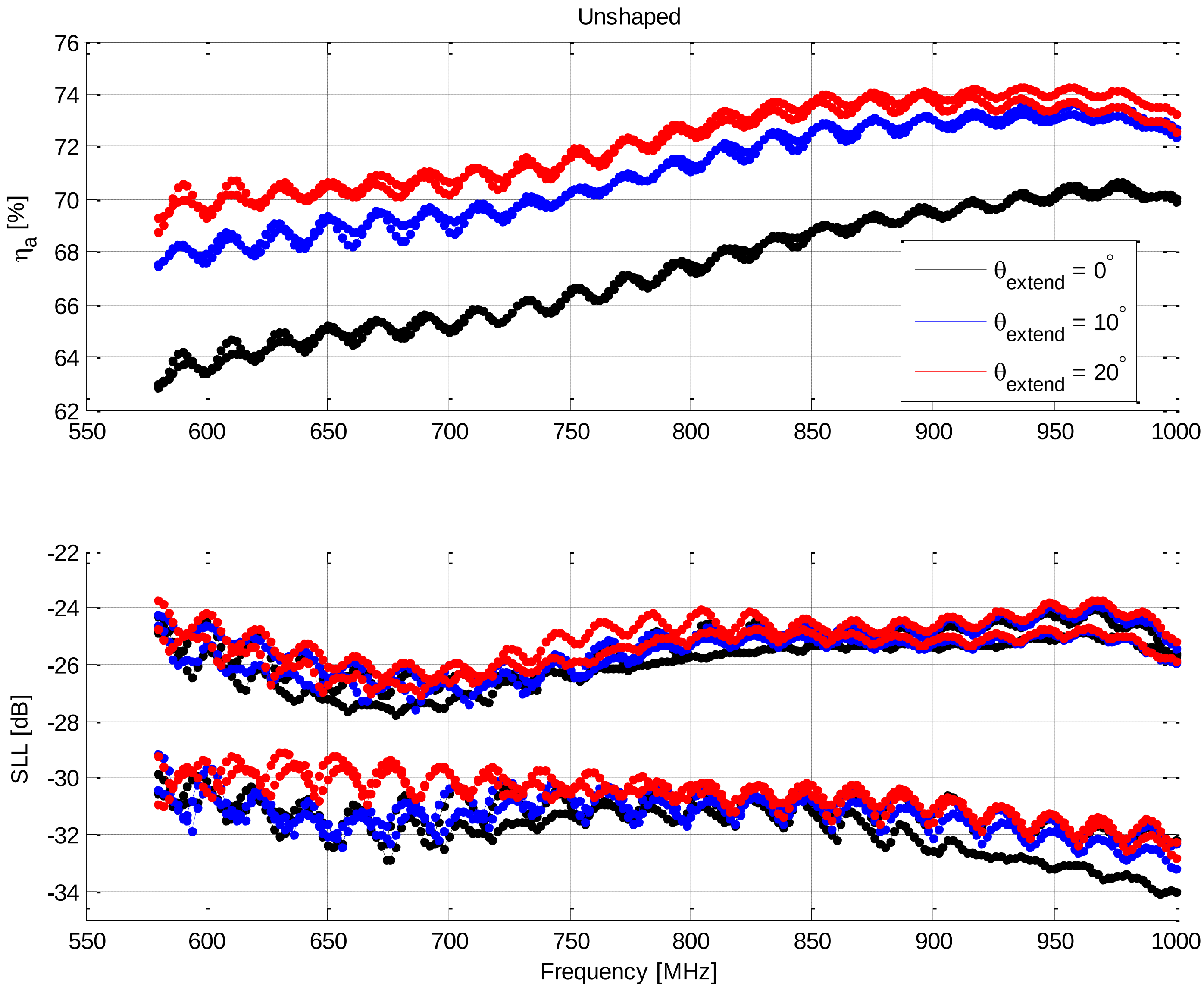
Designing the extension

- Extension primarily to shield spill-over
- Tend to increase gain
- Reduce diffraction ripple
- Increase reflection back to feed
- Increase cross-polarisation
- Need further optimisation

Designing the extension

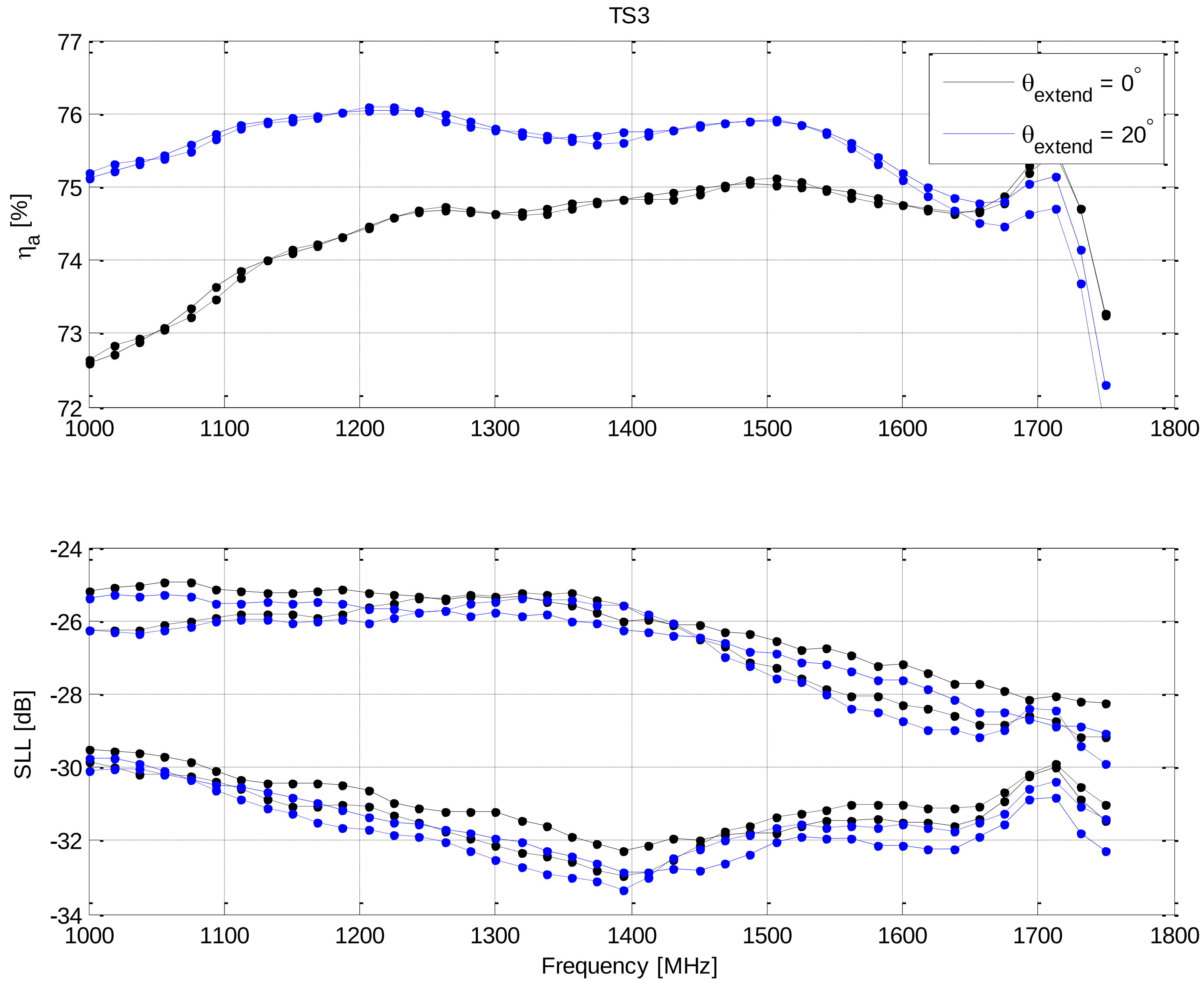


Designing the extension



EMSS

Designing the extension



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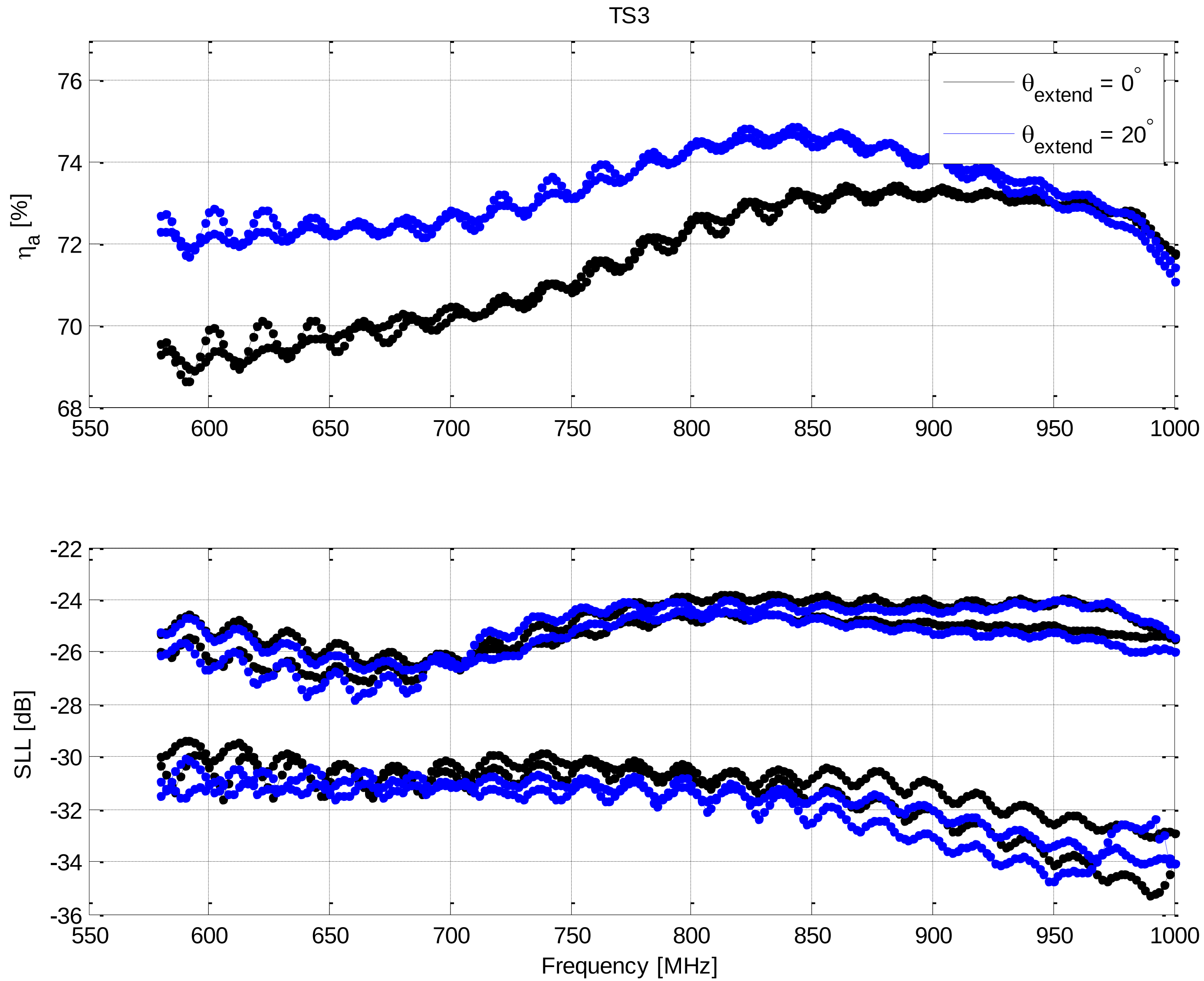
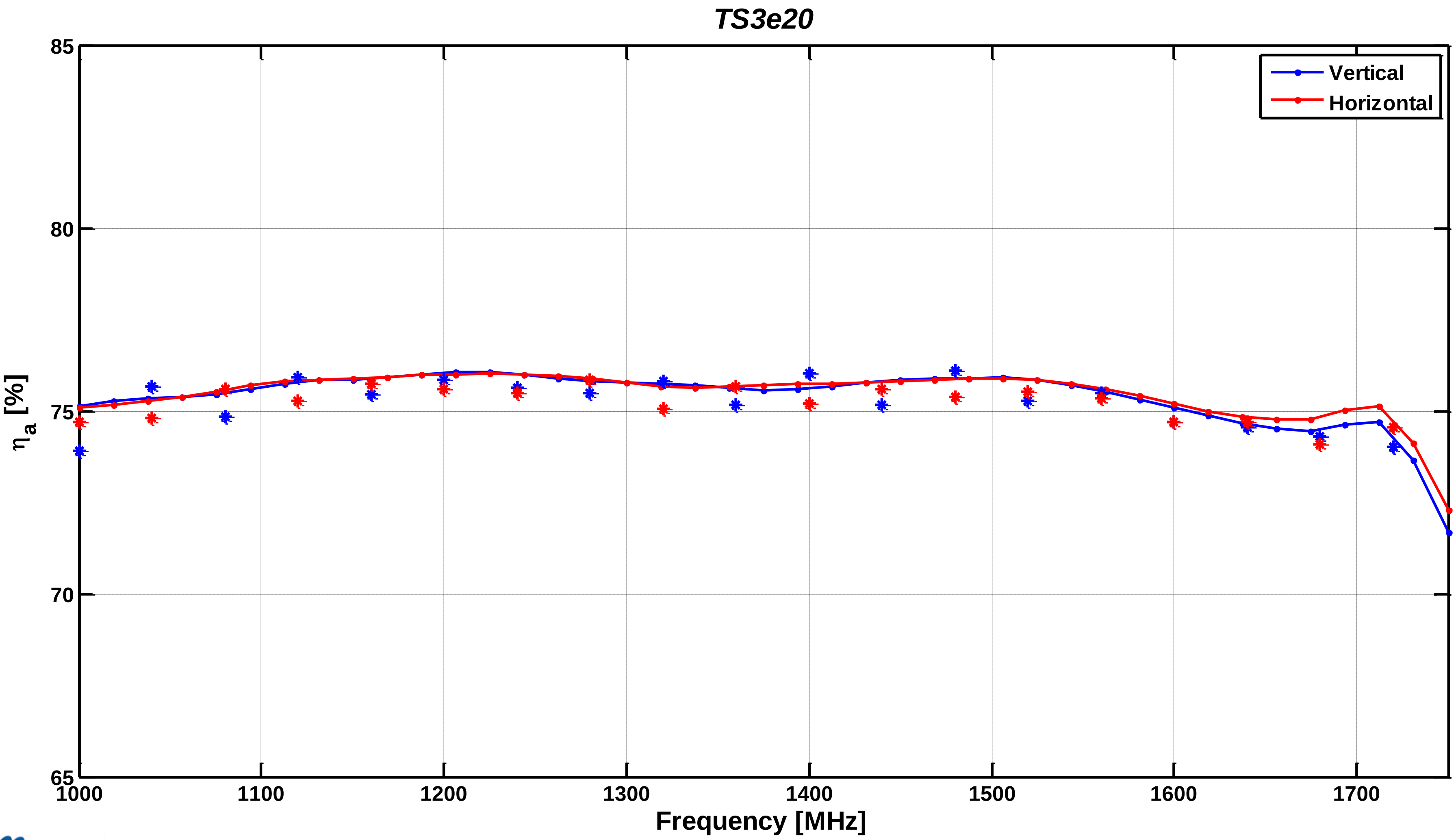


Designing the extension



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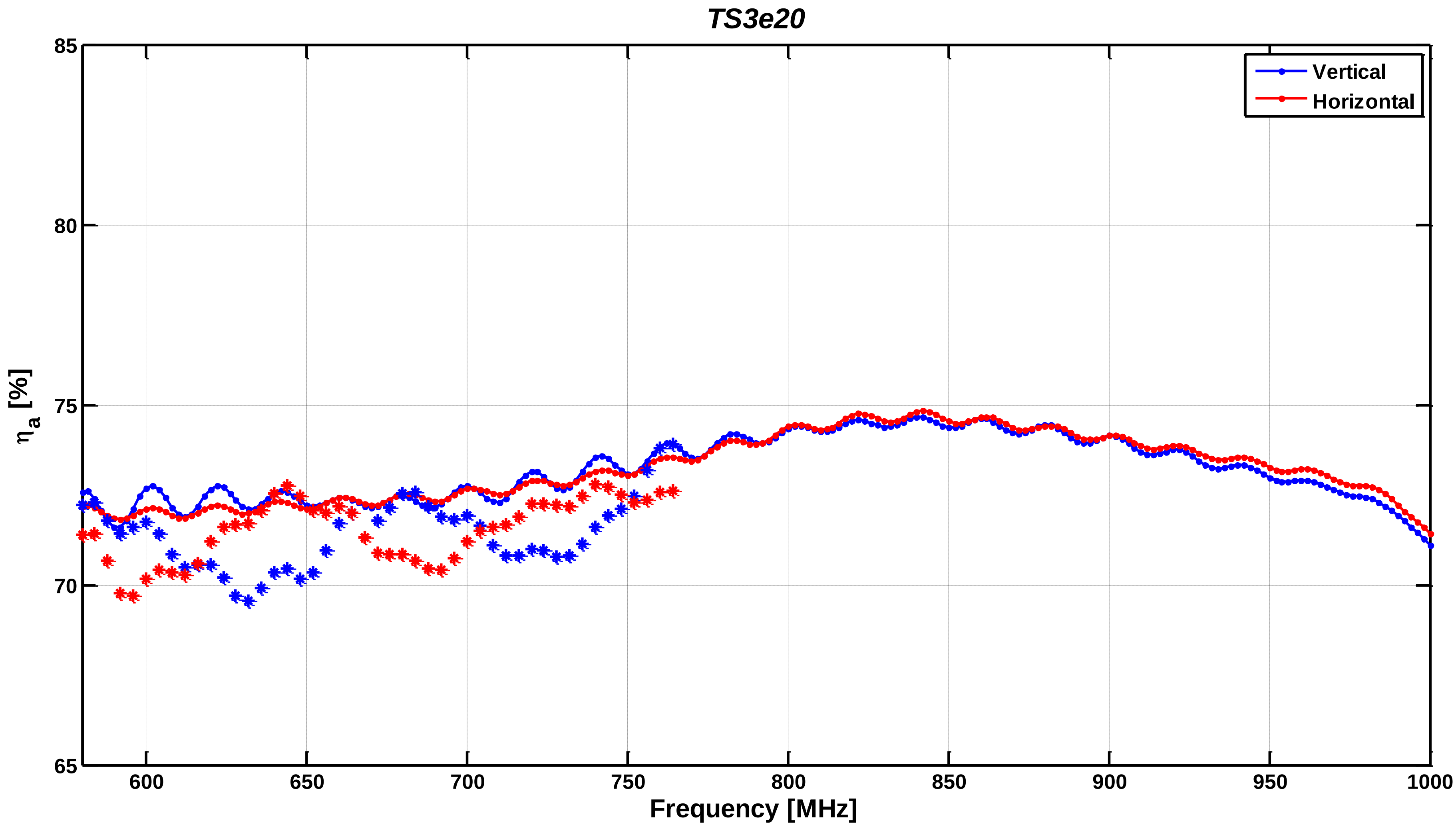

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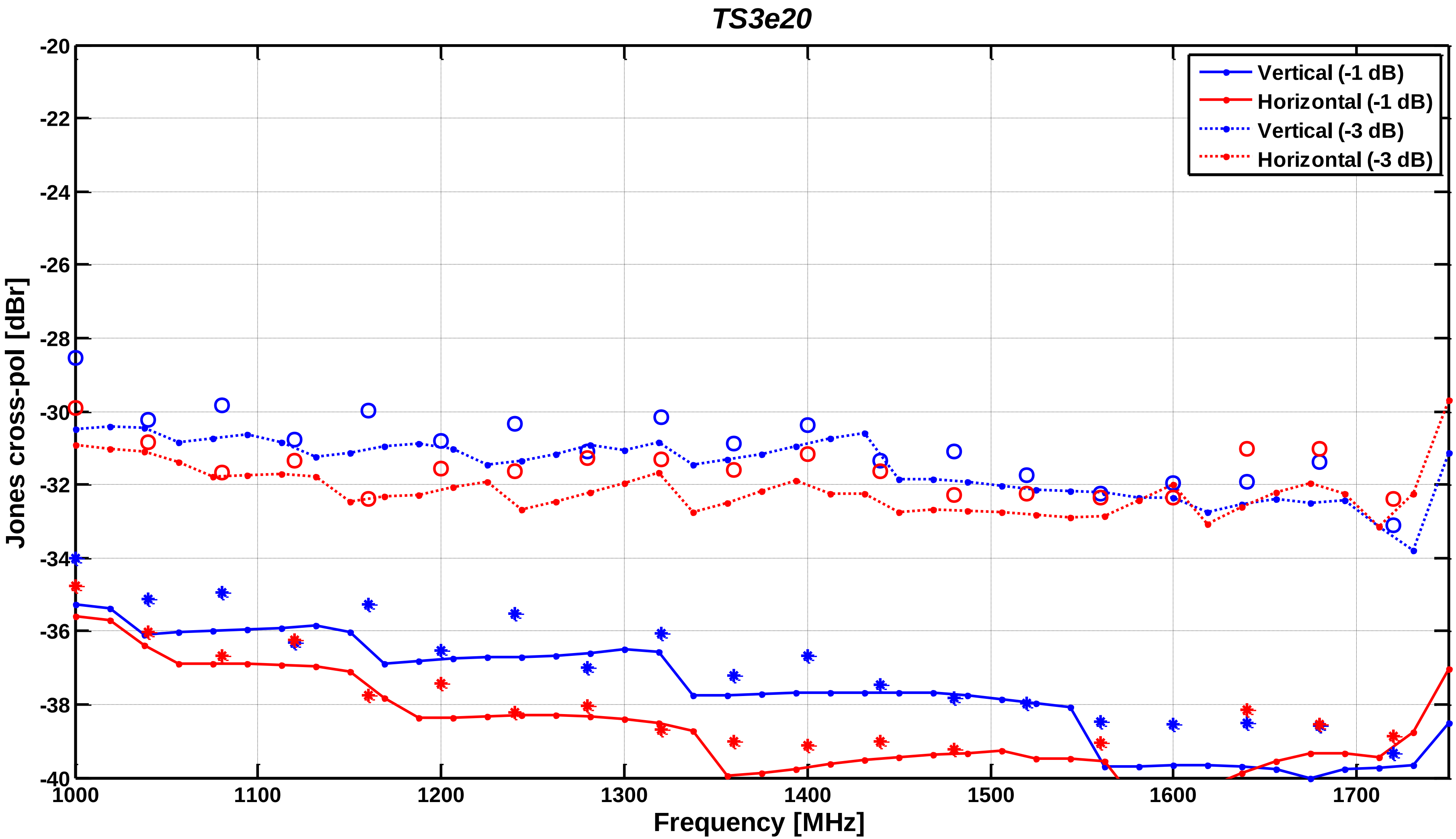

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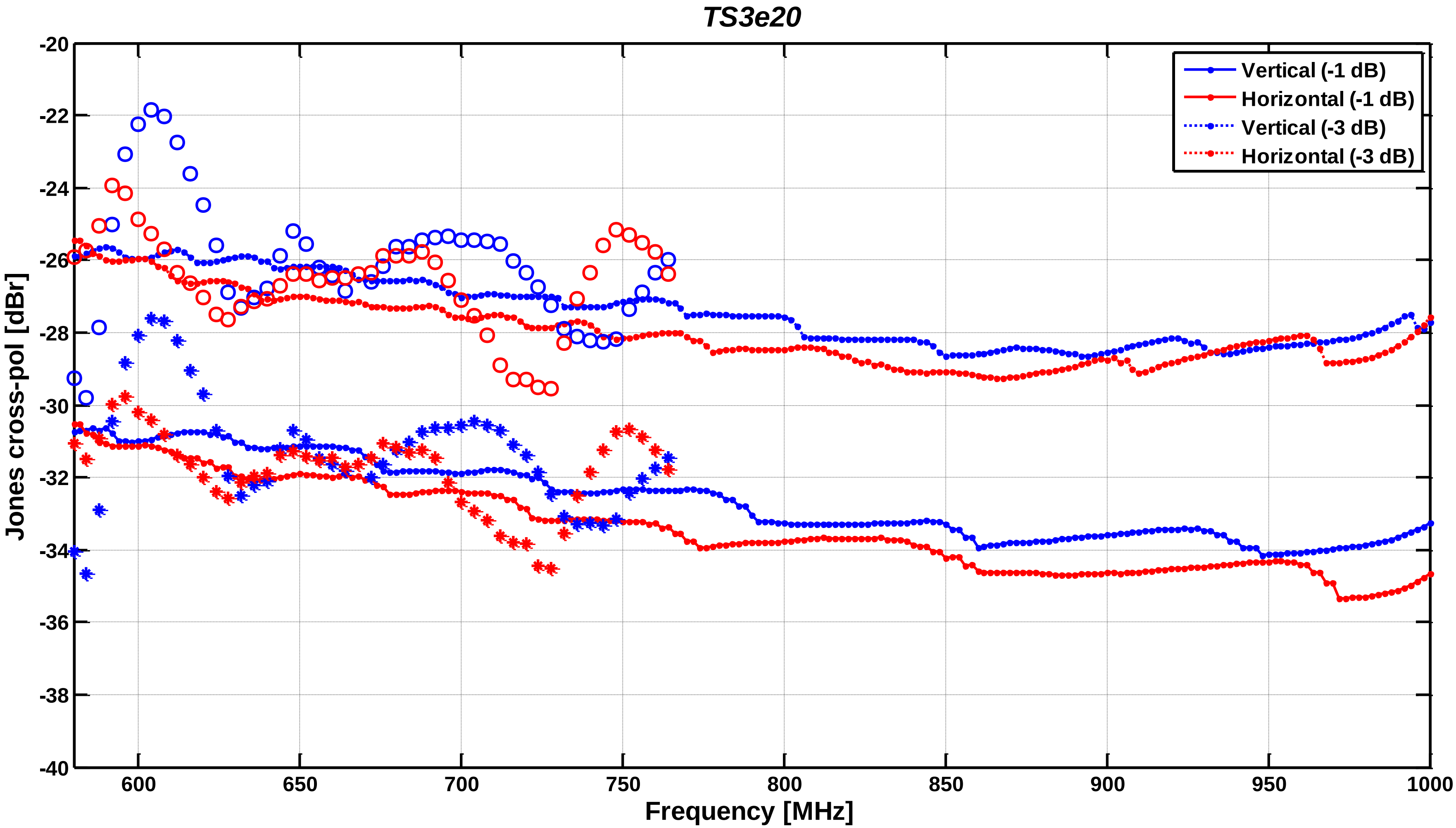
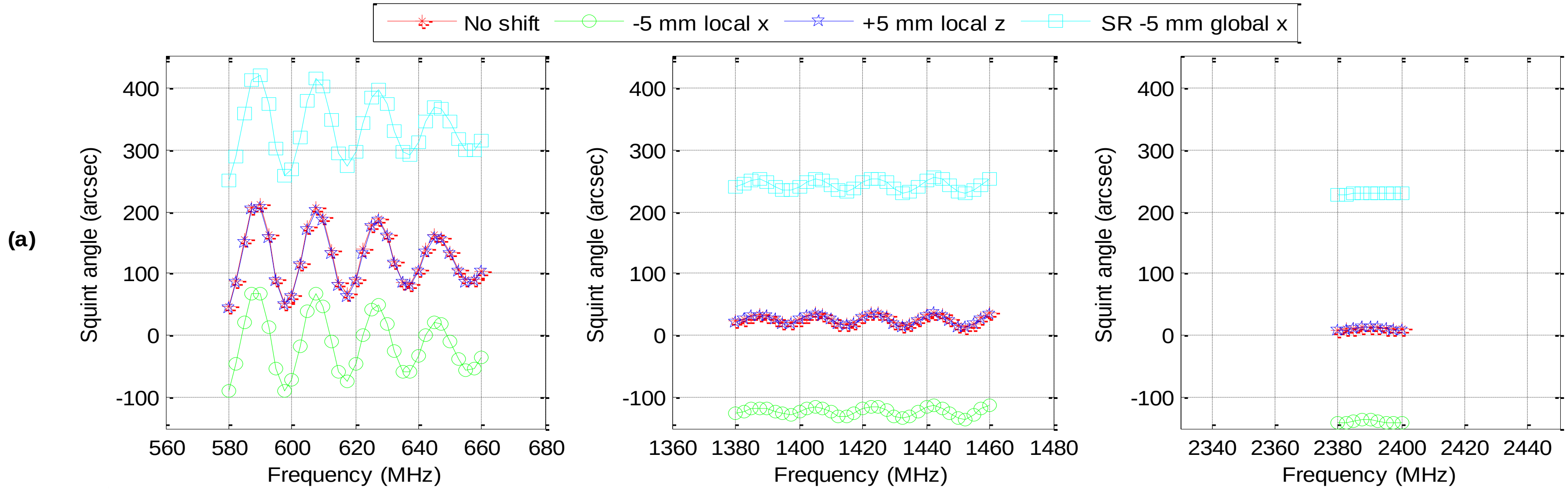


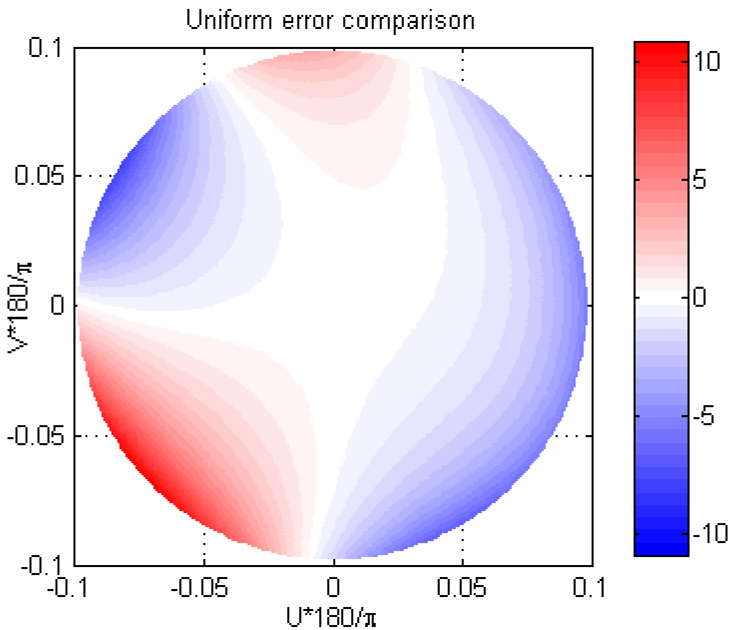
Beam offset

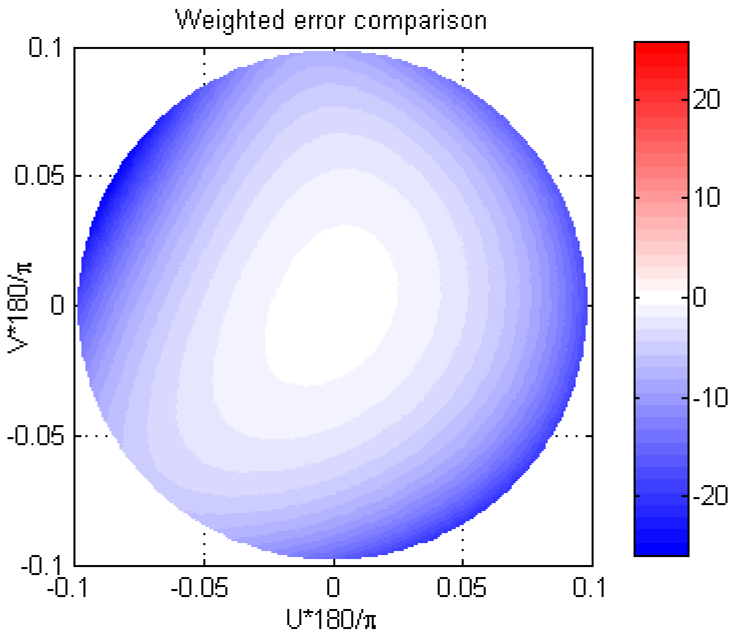
- Beam offset that decrease with frequency
  - Due to reflected angle ≠ incident angle
- Oscillating behaviour
  - Due to diffraction from sub-reflector



Tolerance

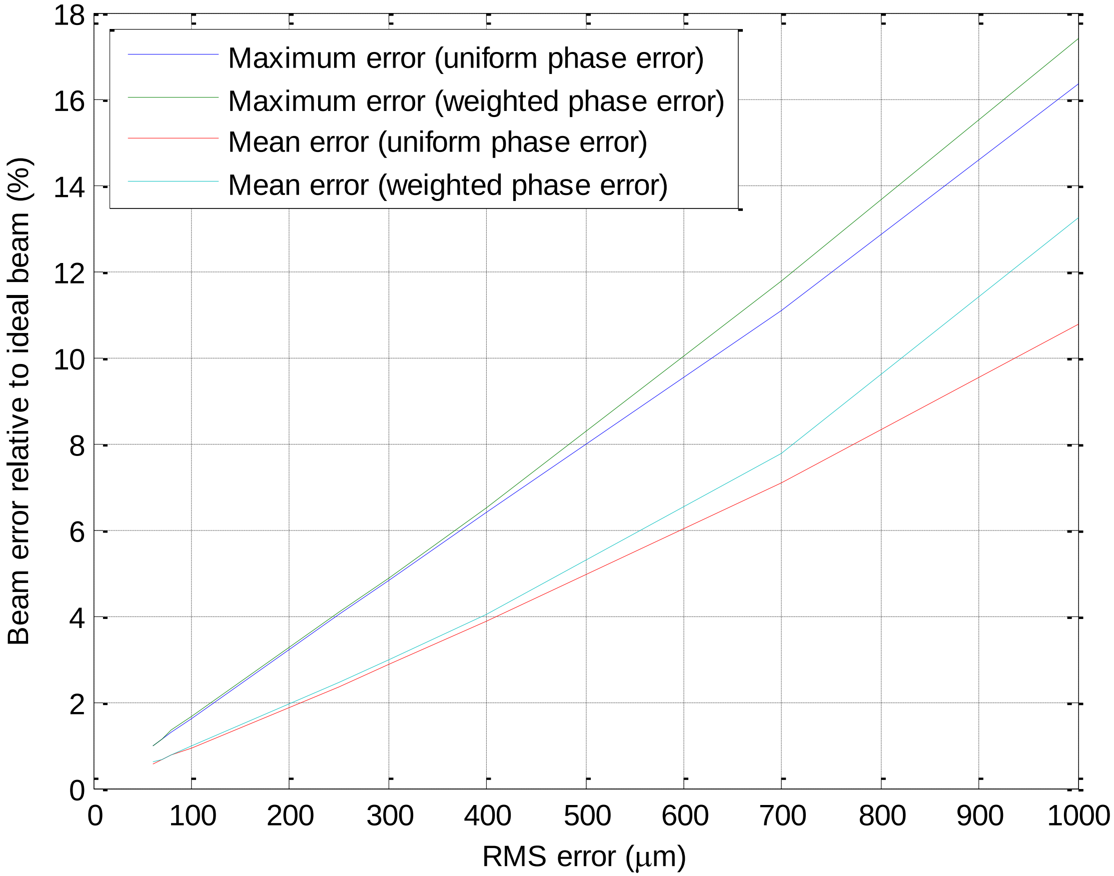
- Surface RMS accuracy
  - Reduce efficiency (Ruze)
  - Cause variation between beams
  - Very frequency dependent (1mm at 14.5GHz)





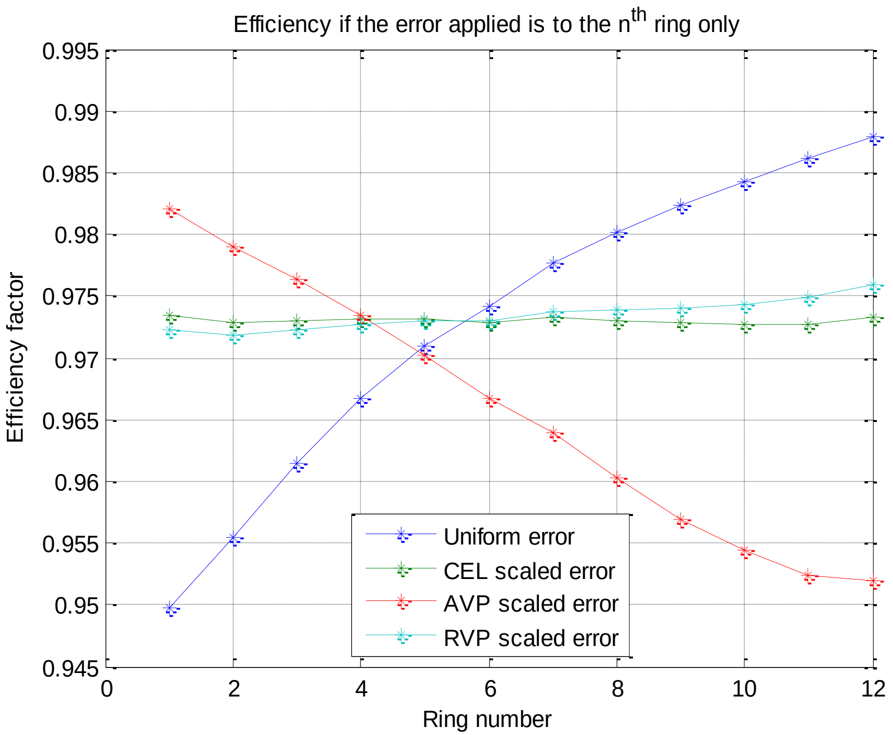
Tolerance

- Requirement for beam similarity



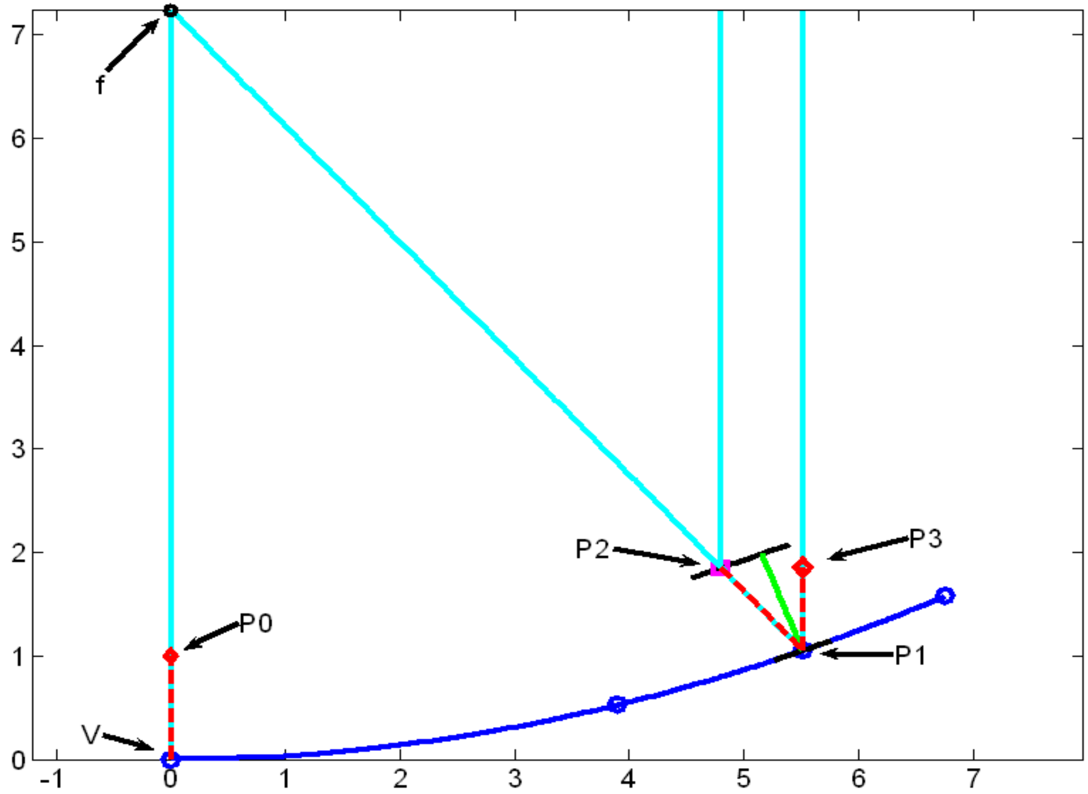
Tolerance

- Reduction in efficiency
- Edges less illuminated than centre
  - Weight the outside less than the centre
  - Kept “loss” per ring constant
  - Similar to weighting the error with the square root of the aperture voltage pattern

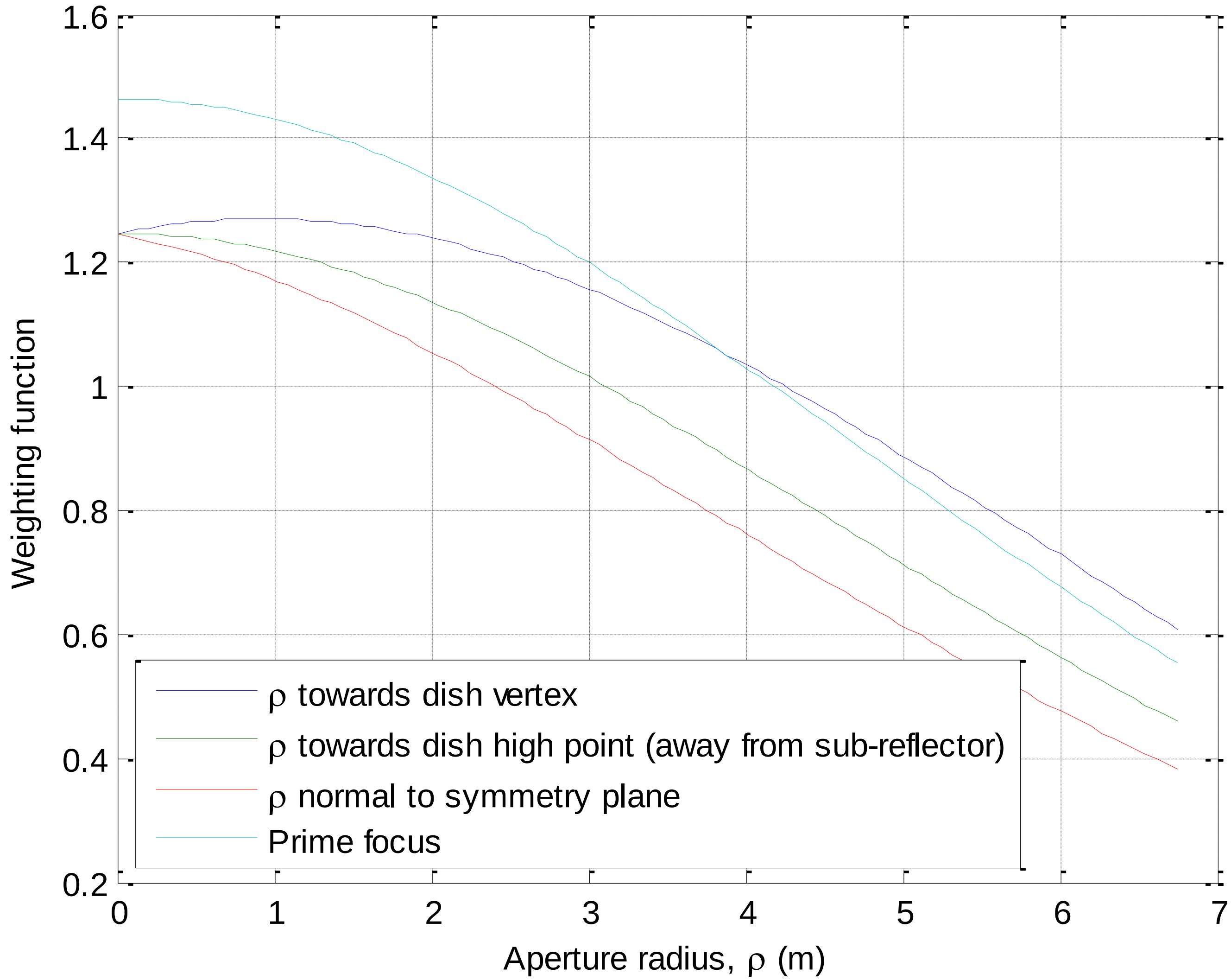


Tolerance

- Phase error due to length
- Oblique incidence



Tolerance

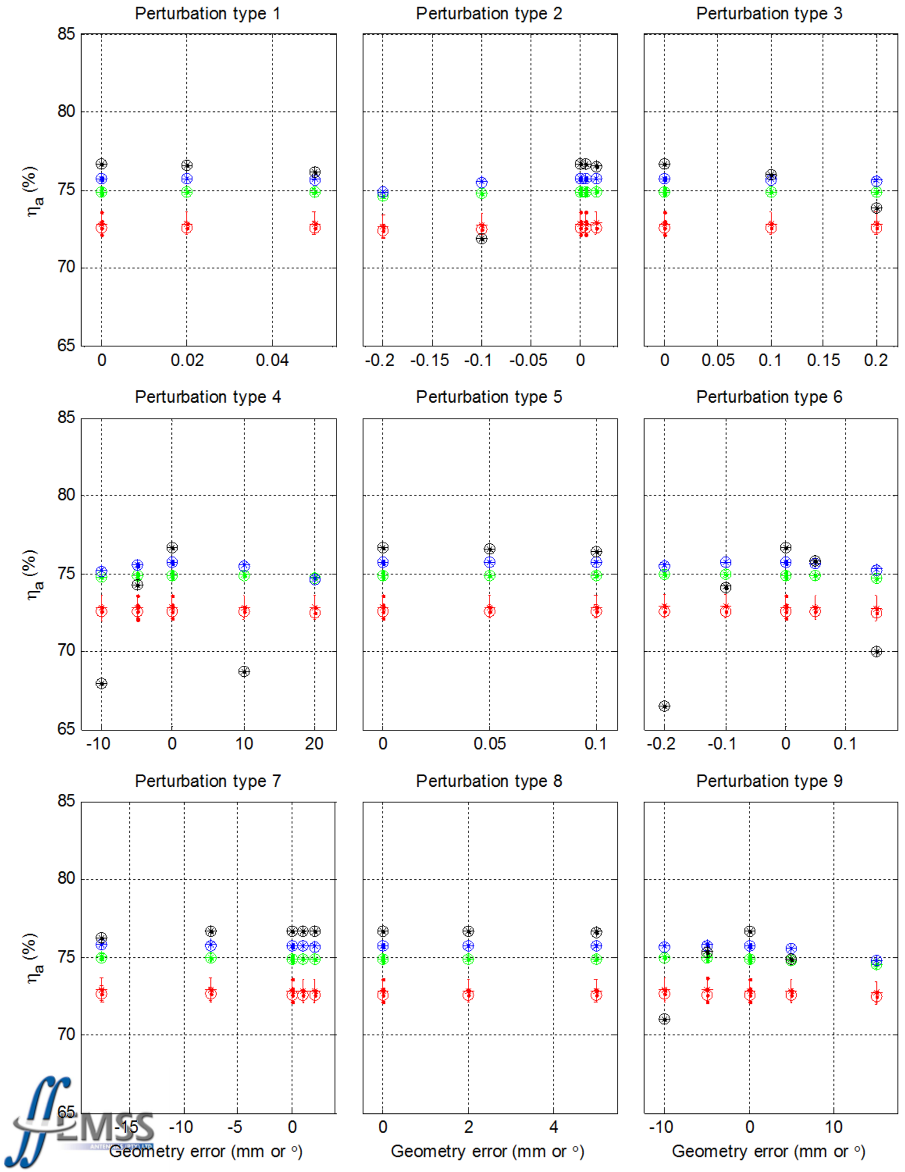


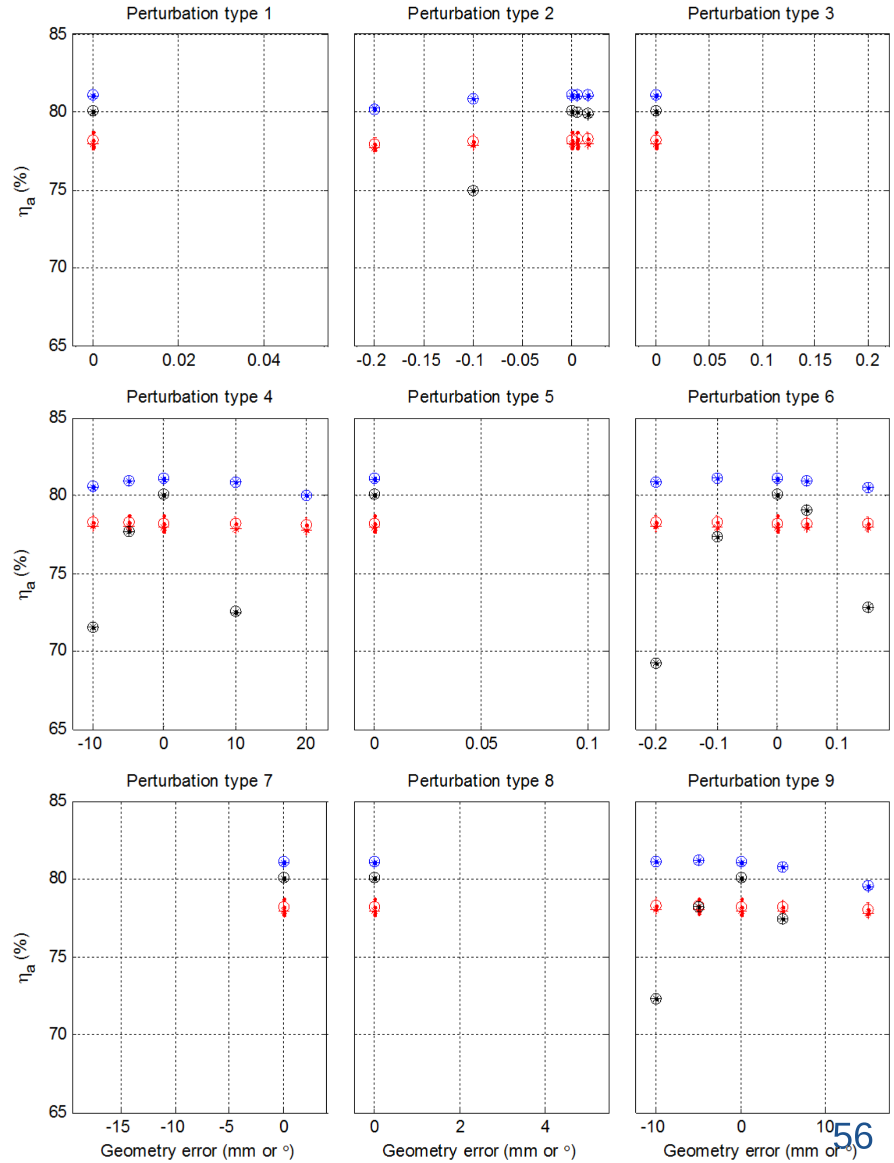
Weighting function
Aperture radius, ρ (m)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
2
3
4
5
6
7
ρ towards dish vertex
ρ towards dish high point (away from sub-reflector)
ρ normal to symmetry plane
Prime focus

Tolerance

- Effect of alignment
  - Sensitivity at high frequency
  - Pointing
- Effect of loading tolerance
  - Pointing
    - Can compensate for gravity, not for wind
  - Sensitivity
  - Beam shape and polarimetric variation

Tolerance (TUE.3 and TSE.3)





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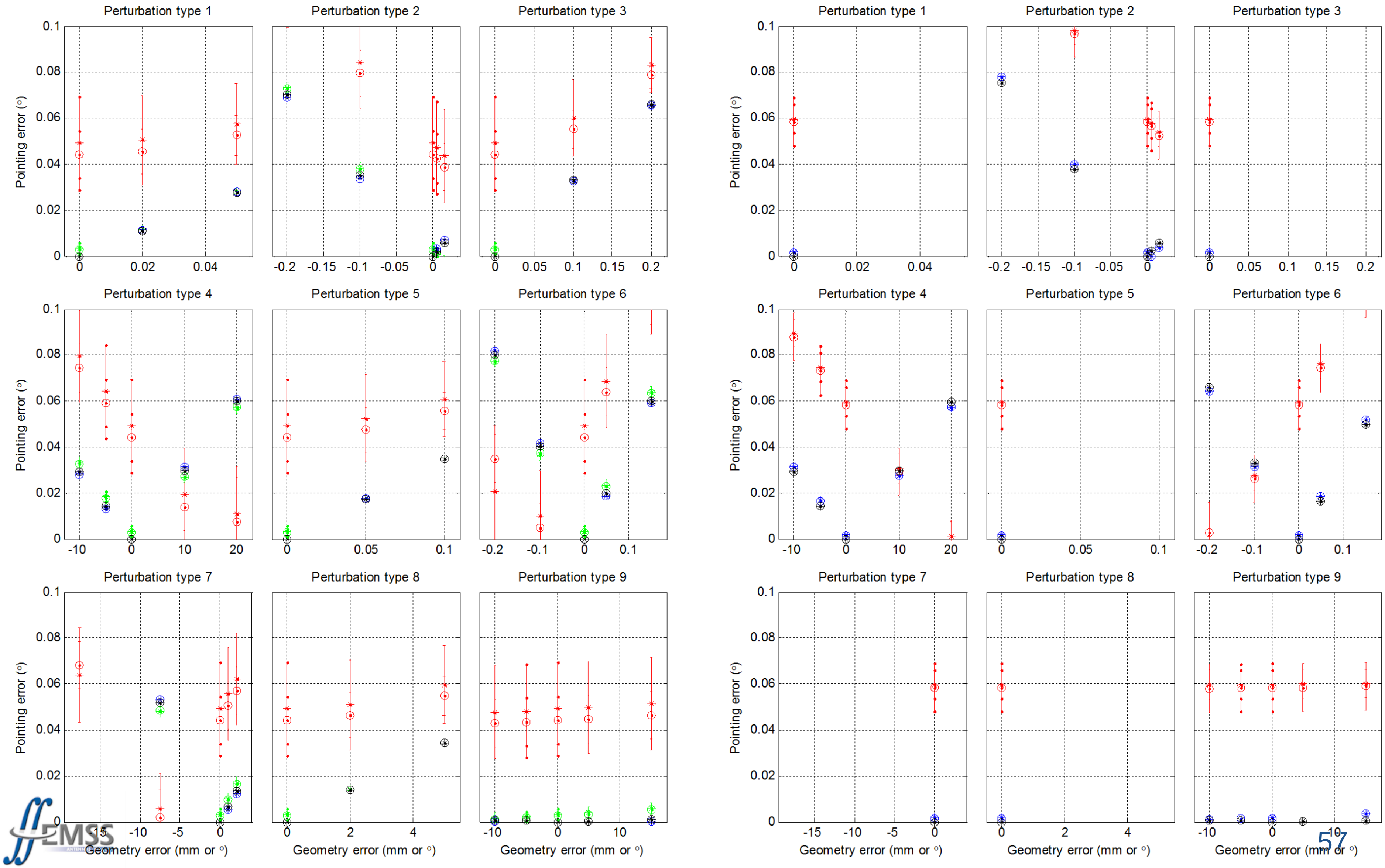

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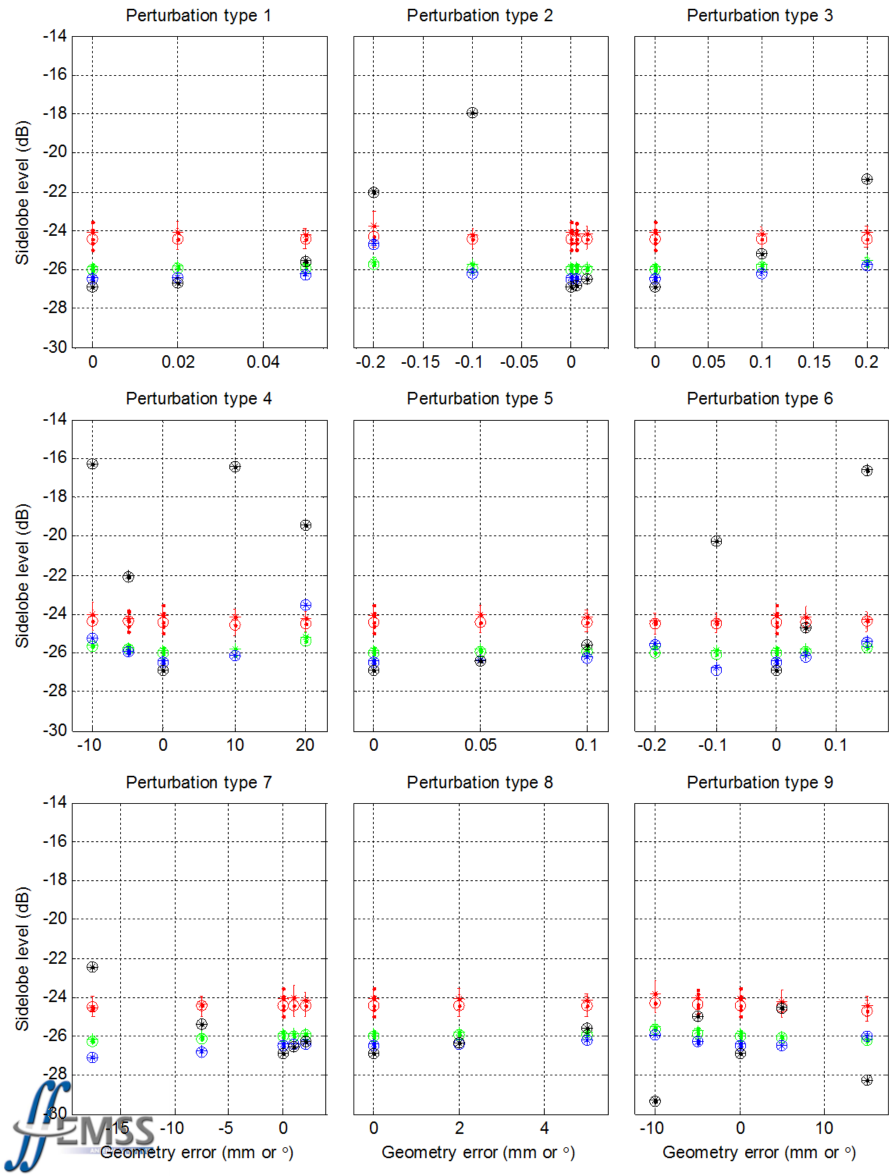

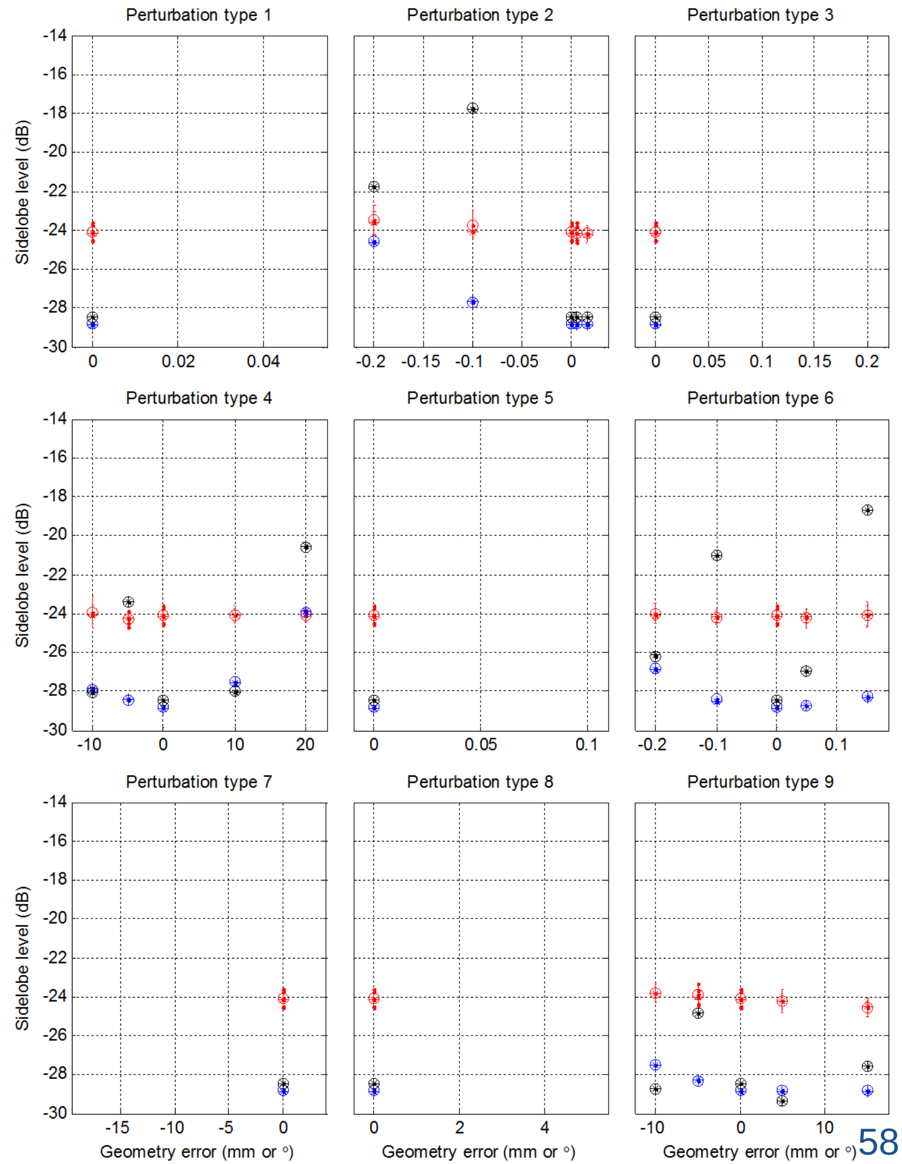

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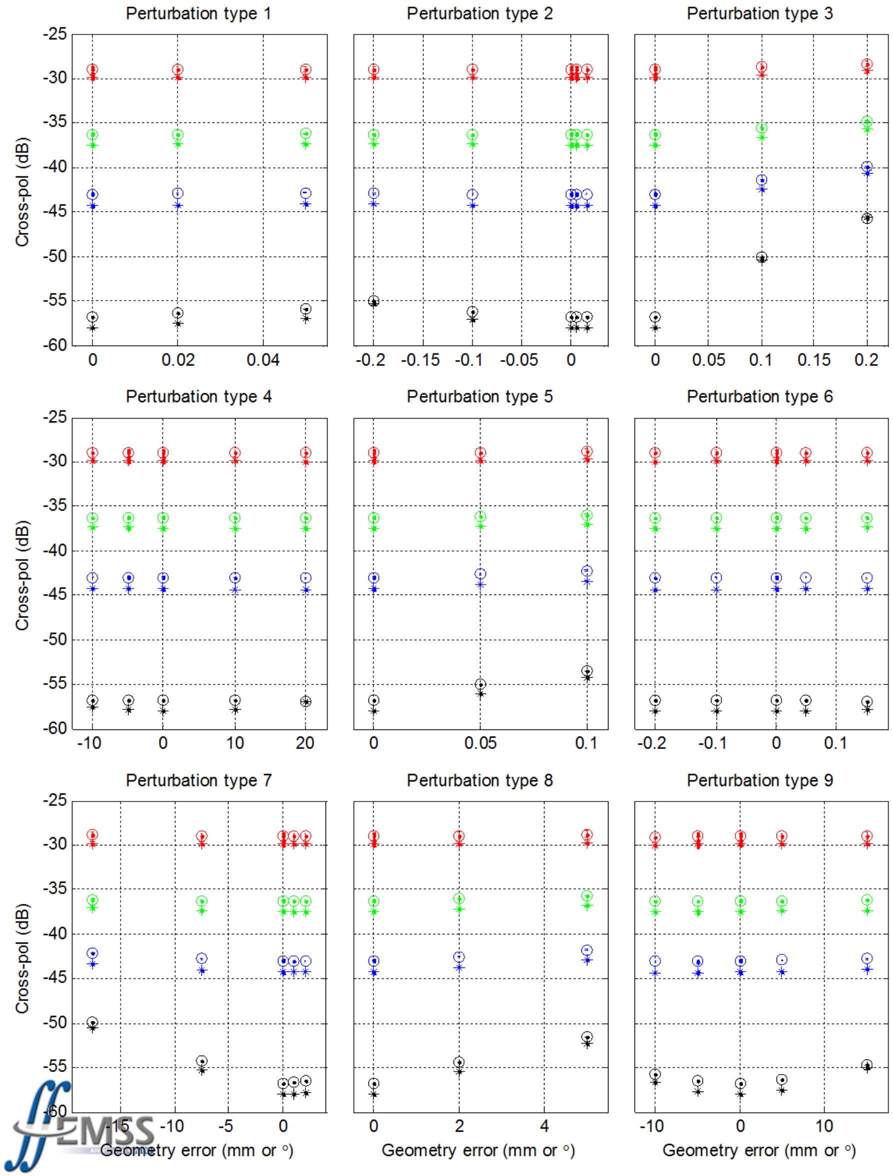
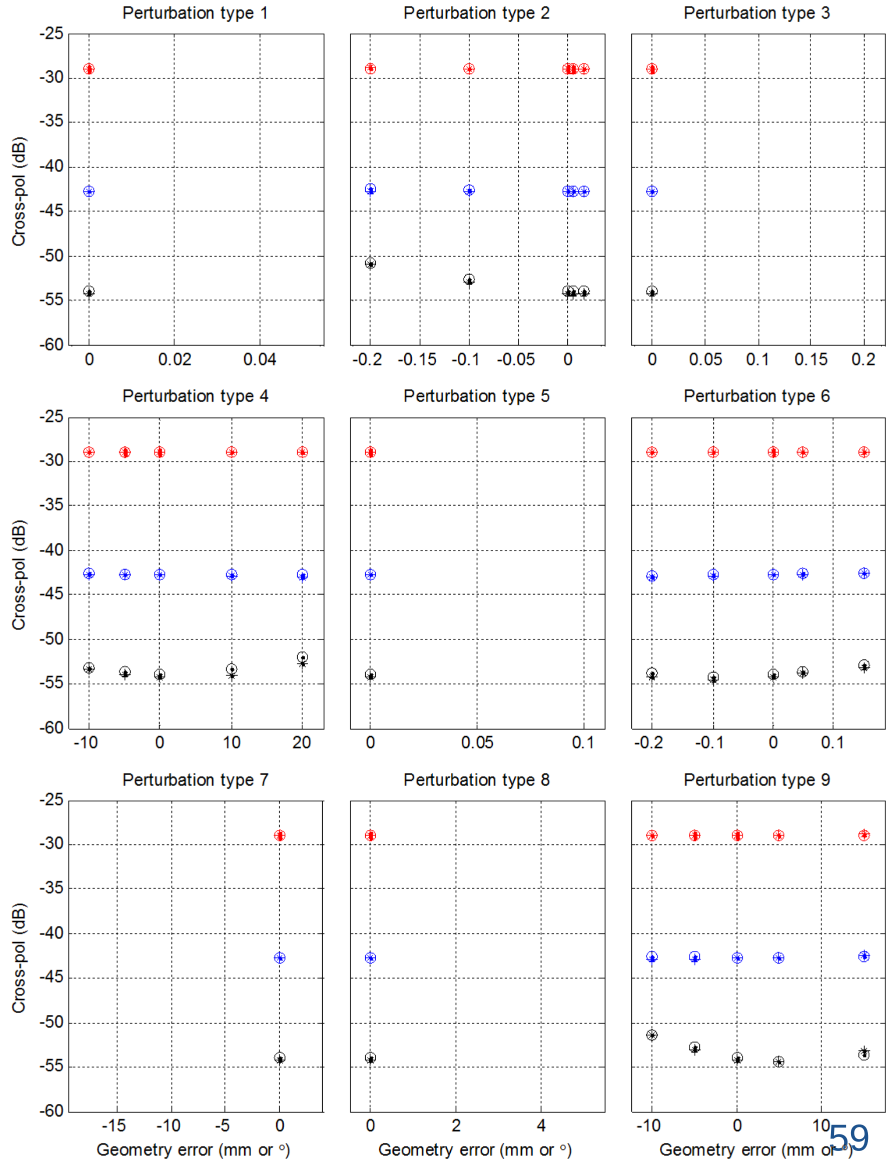




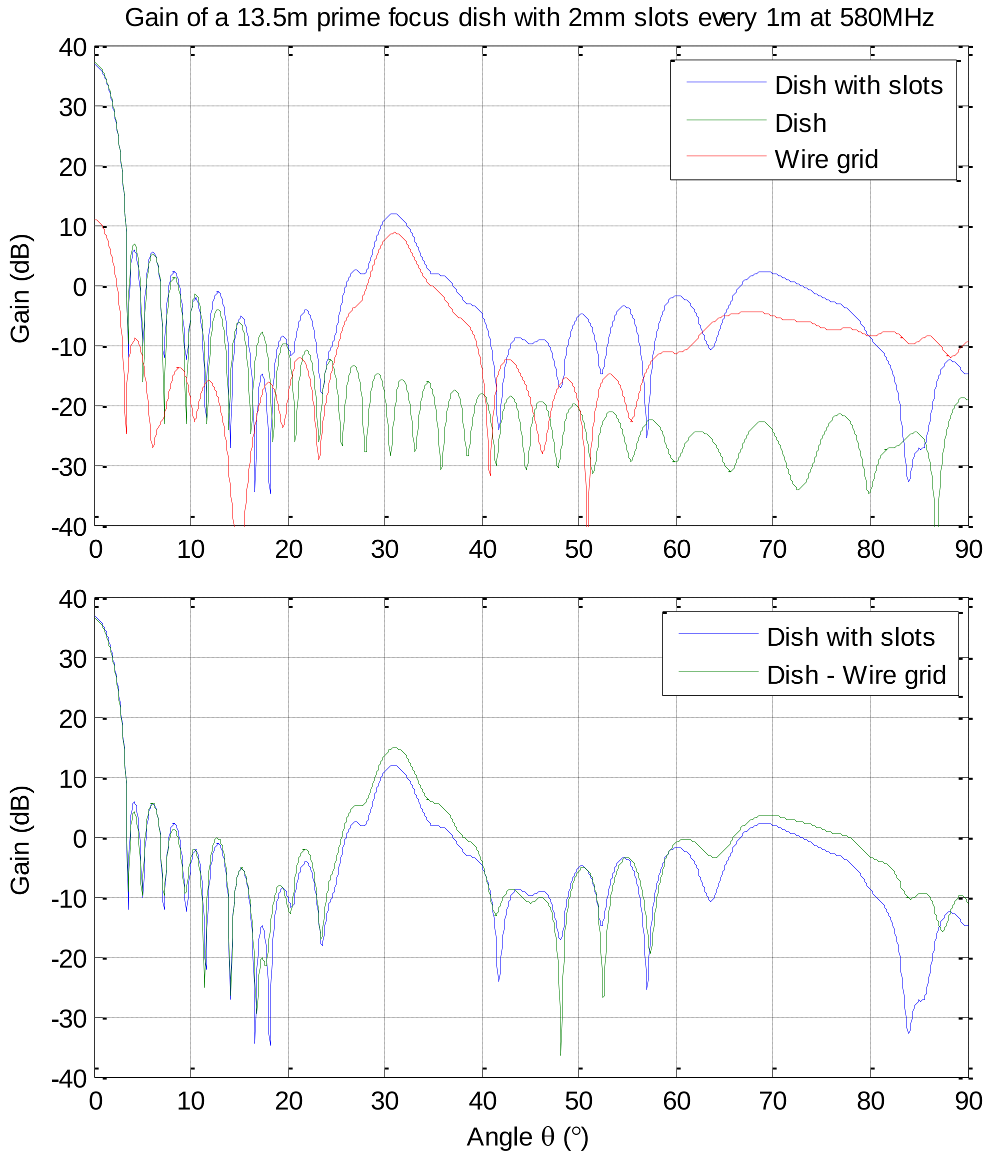
Side-lobe specification

- -30dB side-lobe requirement at 3° from bore sight (to avoid RFI) difficult for UHF
  - More or less the first side-lobe
  - Need interaction here on the advantages / disadvantages

Slots

- Slots between dish panels
- Quarter-wave “connecting” slots
  – Narrow band solutions
- Can model with wire grid
  – 13.5 m prime focus dish with F/D = 0.55
  – 2mm wide slots every 1m (not through centre)
  – MLFMM solution at 580MHz
  – 25 dB side-lobe at 30°
- Duality - need to work with magnetic fields

Slots


Gain of a 13.5m prime focus dish with 2mm slots every 1m at 580MHz
Dish with slots
Dish
Wire grid
Dish with slots
Dish - Wire grid
Gain (dB)
Angle θ (°)

Interpolation

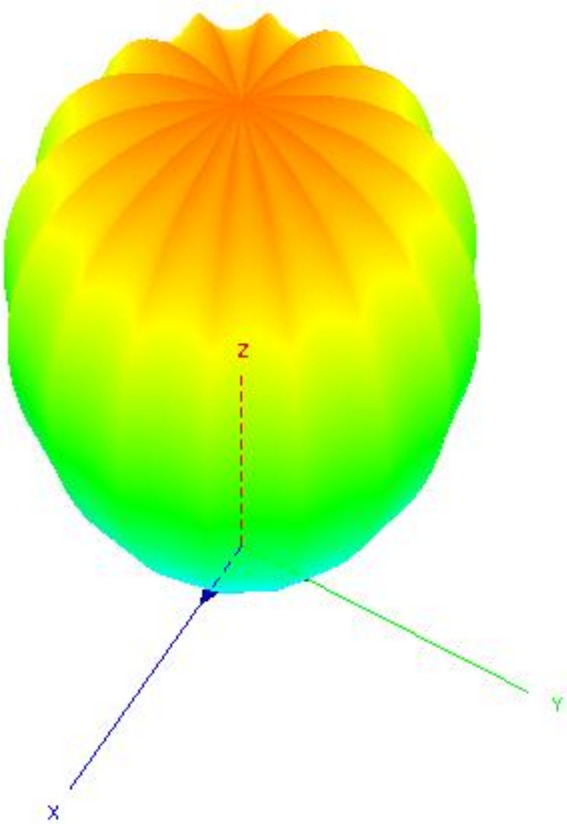
- Beam offset vary rapidly with frequency
  - Causes variation in direction dependent gain
- Base beams from numerical patterns
  - Slow to compute per frequency
  - Large amount of data
  - Need to interpolate
  - Cannot do so on the beam itself

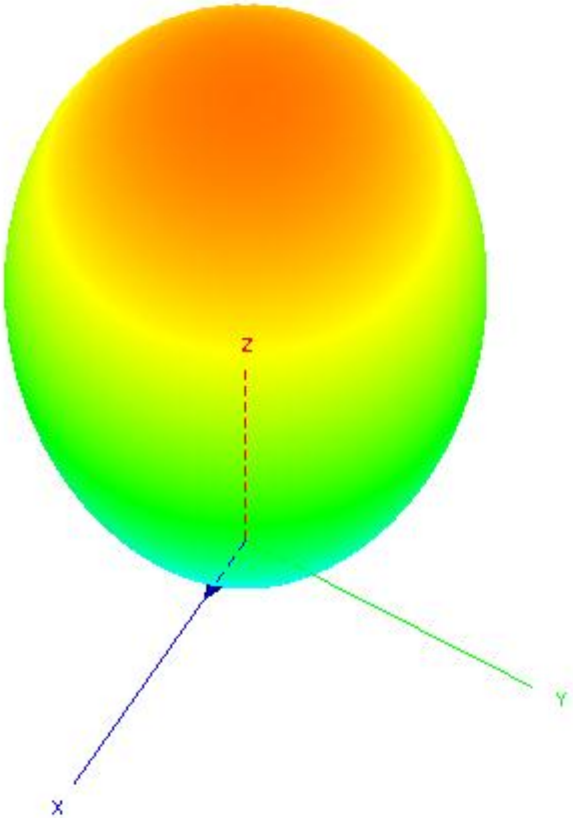
Interpolation

- Interpolation should reflect the physical
  – Propagation terms $e^{-jkL} = e^{-jk'f}$
  – Interpolate between frequencies where $k'f$ is effectively 0° and 90°, i.e. the exponential vary between 1 + j 0 and 0 + j 1
    - Linear interpolation of the real and imaginary components yields 0.5 + j 0.5
    - Linear interpolation of amplitude and phase yields 0.707 + j 0.707 which, is correct in this case
  – Interpolation where the second frequency is effectively $n2\pi + \Delta$ is a problem

Interpolation

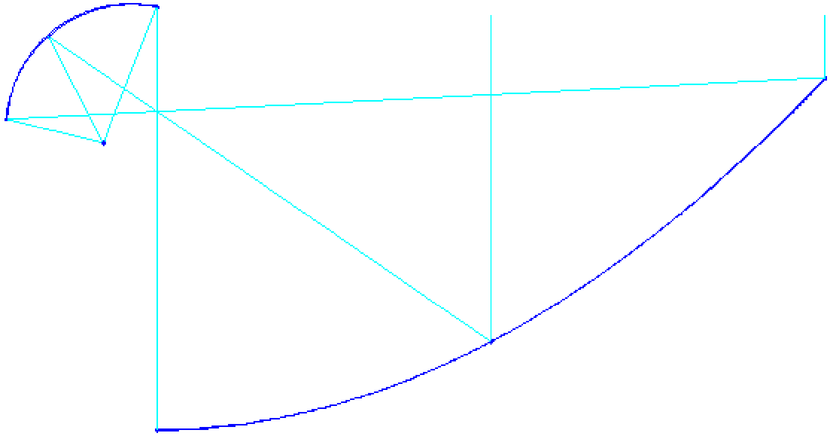
- Interpolating $\theta, \emptyset$ components for linear polarisation on too coarse a grid





Interpolation

- Solved three components of the field
  - Main reflector
  - Feed
  - Sub-reflector
    - Top and bottom are stationary phase points



Contents

Way forward

The near (MeerKAT) future

- Finalise the frequency interpolation
- Determine basis functions for calibration
  - Does this influence the design?
- Trade-off of the antenna beam parameters
  - Aperture efficiency
  - Spill-over temperature (extension design)
  - Side-lobe levels (near and far)
  - Cross-polarisation
  - Beam roundness

Thank you